PERCEPTUAL PLASTICITY IN THE PERIPHERAL VISUAL FIELD OF OLDER ADULTS

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Abstract

Perceptual learning is an important mechanism in the human visual system, and can lead to long-lasting improvements across a broad range of perceptual tasks. In this study we demonstrated how perceptual learning can be applied to improve word recognition in the peripheral visual field of a sample of older individuals. We have shown that improvements in thresholds can be equalised across age, simply by increasing the number of training sessions available to older observers.

Based on this initial finding we further sought to establish a protocol to induce improvements in reading ability for a sample of individuals with age-related macular disease (AMD). As a prelude to this work, we investigated the effects of crowding and fixation instability on similar tasks.

Having suffered damage to their central vision, our target population (individuals with AMD) must use peripheral vision for daily viewing tasks. Peripheral vision is known to be highly susceptible to crowding, the influence of which has previously been shown to strengthen with age. We investigated the relationship between age and crowding on a letter recognition task, and found that (for this task) crowding was age-invariant, implying that this key inhibitor to peripheral visual perception should not have an inordinate influence on learning in our AMD sample.

Our work on fixation stability also led to promising results. We demonstrated that our proxy for fixation instability (a dynamic target or dynamic fixation point) did not adversely affect letter recognition thresholds. Fixation instability is a common issue in AMD, but our data suggests that this may not adversely affect learning on our word recognition task.

The final part of this work has been the implementation of a small study in which we trained a sample of individuals with AMD on our word recognition task. Significant improvements in thresholds were observed, though these did not quite reach the level of an age-matched normally sighted sample.

Nonetheless, the trajectory of the learning curve suggests that further improvements would be possible with extended training sessions.

Crucially, we also observed significant transfer of learning – from the trained word recognition task to an untrained sentence reading task (the MNRead Acuity chart). This is a key aspect of the study, as we are primarily interested in developing training protocols that lead to real-world improvements in visual ability. Improvements on MNRead scores are promising, and suggest that our approach may prove to be a useful starting point in the development of a robust therapeutic protocol.

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Chapter 1: Introduction

1.1 The visual system

The visual system receives, relays and processes visual information through a diverse set of structures. In this section we will describe the basics of this process, as a prelude to a more detailed look at specific visual tasks in later chapters.

1.1.1 The eye

The eye collects light, focuses it, and encodes the first neural signals in the visual system. It has a complex structure, as seen in figure 1.1.

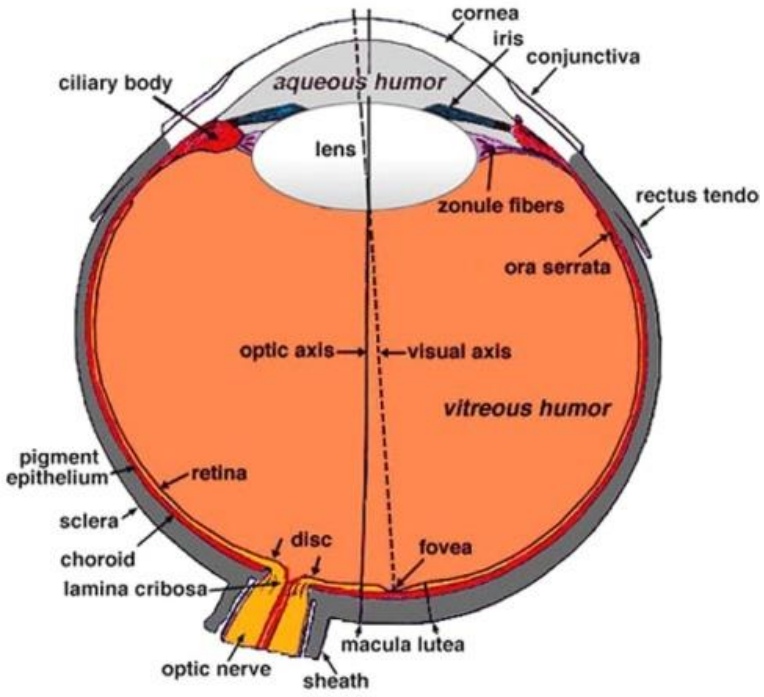

Figure 1.1: Sagittal section of the human eye (Kolb, 2012).

Light enters the eye interior via the cornea and pupil. The pupil is a transparent aperture, the size of which is controlled by the coloured iris (which allows a greater or lesser amount of light to enter the eye). However, it is not simply a passive opening, and has three major optic functions (Slamovits, Glaser & Mbekeani, 2006):

- It regulates the amount of light reaching the retina by varying in size,
- It helps to reduce chromatic and spherical aberrations that are produced by imperfections in peripheral parts of the cornea and lens,
- It can alter the depth of field.

Pupil size and reactivity are both subject to change with age (Loewenfeld, 1979). Upon reaching adulthood, the pupil becomes steadily smaller, while also decreasing in reactivity (that is, the amplitude of the light reflex decreases).

The cornea is a fixed-focus lens that covers the iris and pupil, and is itself covered by a thin film of tears. This provides the initial focusing of light entering the eye. Finally, the sclera (the “white of the eye”) forms the supporting wall of the eye, and is continuous with the cornea.

Within the eye, the lens provides further focusing power, and unlike the cornea it can alter its shape in order to sharply focus light on the retina (accommodation). The pupil also changes size as part of the accommodation reflex, in response to focusing on near or far objects.

Before reaching the retina, light must pass through the tear film, cornea, anterior chamber, pupil, posterior chamber, lens and vitreous chamber. The amount of light reaching the retina is controlled by the iris, but can also be reduced by defects in the lenses and the fluids within each chamber. The image that finally reaches the retina is upside-down and backwards, as a result of its passage through the lens (Fishman, 1973).

1.1.2 Eye movements

In humans, eye movements are used to allow visual stimuli to fall onto the fovea (the site of best visual acuity) and to maintain fixation of moving stimuli at the fovea. A number of different types of eye movements exist.

Saccades are fast eye movements that can occur under both voluntary and reflex control (often accompanied by some head movement in the latter case). If a target is displaced from the fovea, the ocular system can respond

with a latency of 200-250ms. Velocity varies from 30°/s to 800°/s, with durations between 20 and 140ms. However, the velocity is not constant, but instead accelerates to a peak and then decelerates upon approaching the target.

During a saccade, visual thresholds can be elevated by about 0.5 log units (Dell'Osso & Daroff, 2006), a phenomenon known as saccadic suppression. The mechanism of this suppression has been variously suggested to be an active central inhibitory process (Chase & Kalil, 1972), a reduction in retinal image quality due to the rapid movement (Mitrani, Mateef & Yakimoff, 1971), or more recently a reduction in the gain of the visual detector (Guez, Morris, Krekelberg, 2013). The process essentially cancels conscious awareness of environmental motion during saccades (Koerner & Schiller, 1972).

Foveation is also supported by slow eye movements. Pursuit involves continuously fixating a moving target. It has a shorter latency than saccadic movement (125ms). Unlike saccades, pursuit movement is smooth and can be continuously modified on the basis of any slippage between retinal and target velocity. It is, however, often initiated with a saccade to allow the eyes to catch up to a fixated target that has just started moving. Similar to pursuit movement, the vestibuloocular reflex is responsible for correcting eye movements to account for movement of the head (with latencies as low as 15ms).

There are also a set of smaller and corrective eye movements, which further refine eye position. Large saccades are often inaccurate, and can be followed up by further corrective saccades. Smaller microsaccades (with movements less than 1°) have also been observed, as well as microdrifts and tremor. The exact function of these movements is unclear, though it has been variously suggested that they are involved in correcting fixation errors (St. Cyr & Fender, 1969) or in preventing image fade-out (Yarbus, 1967) (see discussion in chapter 5).

1.1.3 From retina to visual cortex

Once light reaches the back of the eye, photoreceptors in the retina convert light energy into electrochemical neural signals. However, the photoreceptors are actually placed below several other parts of the retina – the nerve fibre layer, ganglion cells, amacrine cells and bipolar cells. Further beyond the photoreceptor layer is the retinal pigment epithelium (RPE), which has several functions. It provides nourishment, metabolic support and structural support to the photoreceptors, and also absorbs any light that has passed the photoreceptor layer, preventing unwanted reflections within the eye. Problems in the RPE layer are particularly associated with macular disease.

The physiology and placement of photoreceptors provides the basic structure of the visual system. There are two broad classes of photoreceptors – rods and cones. Cones come in three varieties, which respond optimally to specific wavelengths/hues. Roughly speaking, we have cones sensitive to short-wavelength (blue), middle-wavelength (green) and long-wavelength (red) light. These can operate over a wide range of light intensities, unlike rods which can only operate under low-light conditions. They have no colour sensitivity, and are more sensitive to low light (scotopic conditions).

The placement of photoreceptors is highly skewed. Cones dominate in central vision, particularly at the macula and fovea, and provide excellent visual acuity (Hirsch & Curcio, 1989). There are almost no rods in the fovea, but they dominate in the periphery. From this we can see that central vision is also the area of greatest colour sensitivity.

Signal strength is determined by both wavelength and intensity. Since a single cell cannot transmit information on both of these qualities, the visual system determines them by combining inputs from many photoreceptors. Photoreceptors transmit their signal to bipolar cells, and from there to ganglion cells. Horizontal and amacrine cells provide lateral connections between cells in this layer. Again reflecting the high acuity of the fovea, each

photoreceptor here connects to a single bipolar cell, while bipolar cells are shared in peripheral vision.

Combination of signals at the ganglion cell layer is relatively complex. Generally speaking, inputs form an antagonistic centre-surround receptive field (Kuffler, 1953) (figure 1.2). The firing rate of “”on-centre” ganglion cells is highest when light illuminates photoreceptors that input to the centre of the ganglions receptive field, with darkness on those that input to the surround. The reverse holds for “off-centre” cells. When all of the photoreceptors that input to the ganglion cell are illuminated, they cancel each other out. Crucially, if a light boundary falls on the receptive field (i.e. some inputting photoreceptors are illuminated, some not) then the ganglion cell can signal this local change in intensity. This is the beginning of edge detection, and thus of perception of physical objects.

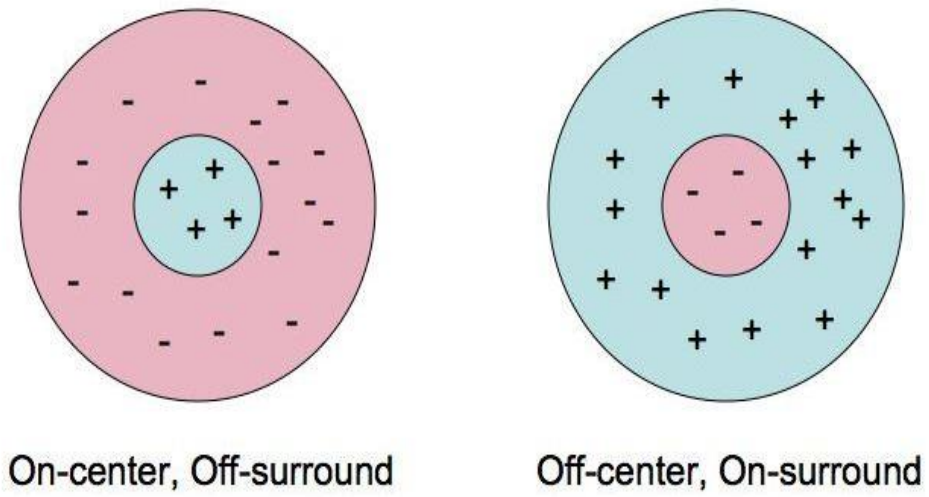

Figure 1.2: On- and off-centre retinal ganglion cell receptive fields (Heeger 2006).

There are three types of ganglion cells, and the subdivision of function between them is continued right through to intermediate neural processing areas. The majority (80%) of ganglions are midget cells. These receive input from bipolar cells with a single input cone cell, and together form the parvocellular (“P”) pathway (Kaplan & Shapley, 1986). They have spectral-opponent receptive fields, and thus allow red-green or blue-yellow colour selectivity. As well as colour vision, they are also specialised for high spatial

acuity (due to the 1:1 relationship of their inputting cones and bipolar cells) and fine stereopsis (Livingstone & Hubel, 1988).

Parasol ganglion cells form a further 10% of ganglion cells, and together form the magnocellular ("M" pathway). They are more common in peripheral retina, and receive inputs from multiple bipolar cells. Their numbers in the periphery are roughly equivalent to the number of midget cells, though parasol cells have a much larger receptive field and lower spatial resolution (Croner & Kaplan, 1995). They are organised for spatial opponency with centre-surround structure (edge detection), and are responsible for low spatial resolution, motion detection, and coarse stereopsis (Livingstone & Hubel, 1988).

Other types of ganglion cells are less well understood. Koniocellular cells may support colour vision in some way. A further cell type is directly activated by light (Hattar, et al., 2002), and may be responsible for the light reflex of the pupils, and for mediation of circadian rhythms.

The axons of the ganglion cells travel through the optic nerve towards the lateral geniculate nucleus (LGN) of the thalamus. At the optic chiasm, information from each half of the retina that views the same portion of visual space is brought together. That is, (for example) the right nasal ganglion cells cross over to join the left temporal ganglion cells from the left eye. The combined axons then carry on through the optic tract to the LGN. The LGN on each side of the brain thus receives input from the ipsilateral temporal retina and the contralateral nasal retina.

The LGN is retinotopically organised, and is arranged in layers with monocular inputs. Two layers receive input from parasol ganglion cells, and another four layers receive input from midget ganglion cells. However, the LGN does not simply receive passive input from the retina. Retinal ganglion cells only account for 5-10% of synapses in LGN (Van Horn et al., 2000), with the remainder accounted for by modulating connections from other areas of the

thalamus and visual cortex. LGN thus modulates the flow of information based on the present behavioural state (Snowden et al., 2012).

1.1.4 The visual cortex

The optic radiations project from the LGN to visual cortex, maintaining their retinotopic arrangement. The macula is significantly over-represented in the retinotopic map in the primary visual cortex (V1). Though it comprises only the central 10° of the visual field (2%), it occupies 60% of the cortical map (Horton & Hoyt, 1991). This cortical magnification leads to extremely high central acuity and spatial resolution for this region.

In V1, neurons with monocular afferents are arranged in ocular dominance columns (Gilbert & Wiesel, 1989). Each column has a preference for stimulus orientation, stimulus size, eye of origin, etc. Nearby columns generally have similar, but not identical, preferences, with preference growing more different with increasing distance.

Neurons in V1 are selective for orientations of luminance contrast, and also process colour, brightness, and direction of motion (Tootell et al., 1988). They are particularly good at contour detection because they have receptive fields with elongated on-centres, which are comprised of the on-centre inputs of multiple ganglion cells. Edges that align with the on-centres of these ganglion cells thus strongly activate the associated V1 neuron.

The magnocellular/parvocellular split is also present in V1, with neurons from each pathway synapsing in different parts of layer 4. This split is also reflected in the dorsal and ventral processing streams, which transmit signals to higher processing areas (Ungerleider & Mishkin, 1982).

The ventral stream (the “what” pathway) is associated with information related to object recognition. It begins in the same part of layer 4 of V1 that is targeted by the parvocellular pathway from LGN. From there it projects to colour and form regions of V2 (Sincich & Horton, 2002), and from there to V4 and higher processing areas.

The dorsal stream (the “where” pathway) is associated with information related to visuospatial processing, and has a much lower latency than the ventral stream. It projects from the part of layer 4 of V1 that is targeted by the magnocellular pathway (motion-sensitivity) and projects to V2, V3 and subsequently to V5 and higher areas. Here it is involved in higher-order analysis of motion signals (Tootell, et al., 1995).

Information from both streams is ultimately sent to higher areas, such as entorhinal cortex (associated with the formation of long-term visual memories), amygdala (emotional valence of visual stimuli) and prefrontal cortex (visual working memory).

1.1.5 Anatomical factors affecting peripheral vision

Having covered the basics of the visual system, we now turn our attention to some anatomical and functional factors that are important for our research.

Peripheral vision is impaired by a number of anatomical factors relative to the macula. The macula describes the whole foveal area, including the foveal pit, foveal slope, parafovea and perifovea. Central retina, close to the fovea, is thicker than peripheral retina due to the increased density and clustering of photoreceptors. Here there are a wide variety of receptive field sizes within close proximity of one another, which project forward to a range of smaller and larger cortical receptive fields in V1. The smaller receptive fields tend to have a low number of ganglion inputs per V1 neuron, while the larger ones have numerous inputs.

However, the density of photoreceptors (and number of available receptive fields) decreases with increasing eccentricity (Osterbergy, 1935; Curcio, Sloan, Kalina & Hendrickson, 1990), as does the density of the corresponding ganglion cells (Perry, Oehler & Cowey, 1984). Spatial summation occurs over larger areas, meaning that only larger receptive field sizes are available to process signals. These project forward to similarly large cortical receptive fields that are dependent on the coarse sampling resulting from peripheral

ganglion cell density (Westheimer, 1984). These factors combine to ensure that increasing eccentricity leads to reduced sensitivity and acuity.

This reduction in sensitivity is not uniform across the peripheral retina. The distribution of rods and cones is skewed, with greater numbers in the superior nasal retina relative to the inferior temporal retina (Osterberg, 1935). This is also true of retinal ganglion cells (Van Buren, 1963), which extend further on the nasal than peripheral side of the visual field. This contributes to the characteristic foreshortening of the nasal periphery.

Many studies of peripheral vision neglect the effects of peripheral defocus and optical quality. Optical quality itself can be poorer in peripheral vision (Jennings & Charman, 1981). Defocus is also an issue. Most patients in clinical settings are corrected for foveal refractive error, but this may be inappropriate because peripheral refractive error can be quite different (and can vary with eccentricity) (Frankhauser & Enoch, 1962; Mutlukan, 1994). Light may be refracted inappropriately through peripheral parts of the cornea and lens, and not be focused correctly upon reaching peripheral retina. It is conceivable that in some cases correcting foveal refractive error may actually worsen peripheral refractive error, by further altering any pre-existing refractive error.

1.1.6 The case of contrast sensitivity

We have already touched on contrast sensitivity earlier in this report. However, some further detail may prove useful. Spatial contrast sensitivity is a crucial aspect of our visual ability. Clinical assessments of vision often use black letters on a white background. However, these high contrast stimuli do not reflect the natural, variable contrast environment that we are required to interpret in our daily lives. Understanding how we perceive scenes of varying contrast is therefore crucial.

In the lab, grating patterns are often used to assess contrast, where contrast is generally expressed as the differential intensity threshold of the grating. That is:

$$\text{Contrast} = (L_{max} - L_{min}) / (L_{max} + L_{min}) \quad (1.1)$$

The spatial frequency of such a pattern is the number of cycles per degree subtended at the eye, where each cycle is equal to one light region plus one dark region of the sinusoidal grating. This highest spatial frequency that is discriminable at the fovea is approximately 60 cycles per degree, roughly equivalent to the physical acuity limit imposed by receptor spacing and optical blurring (Williams, 1985; Banks, Geisler & Bennett, 1987).

By finding a threshold for contrast at each spatial frequency of the grating, we can derive a contrast sensitivity function. A full function shows that we achieve peak sensitivity for high contrast gratings at intermediate spatial frequencies. By altering spatial frequency and contrast independently, this technique allows us to assess visual acuity, contrast sensitivity, and the interaction between them.

Our visual system actually enhances perceived contrast at luminance borders. Uniform illumination does not lead to maximal firing rates due to lateral inhibition mechanisms, such as inhibitory connections between adjacent neurons. Inhibition of constant-luminance scenes thus serves to exaggerate edge detection.

It seems likely that the visual system processes edges, sinusoidal gratings and other stimuli through spatial frequency channels (Blakemore & Campbell, 1969). Each channel has a preferred spatial frequency to which it responds maximally, though it will also respond to neighbouring spatial frequencies.

As well as spatial contrast sensitivity, we can also describe a temporal contrast sensitivity function (De Lange, 1958). This plots contrast against temporal summation, or 'flicker'. The critical flicker fusion frequency (CFF) is that frequency at which an intermittent light source appears as a continuous light. The CFF is affected by both light intensity and size of the stimulus. The temporal contrast sensitivity function plots the contrast of the stimuli against the CFF, and indicates that the eye is most sensitive at temporal frequencies

of 15-20 Hz under high luminance conditions. The CFF peaks at roughly 30-60 Hz (Hart Jr, 1992).

The CFF is partly determined by the temporal properties of ganglion cells. We have discussed spatial summation of ganglion cells, but these cells also have a critical duration that limits the time over which signals can be integrated (Hart Jr, 1992). If enough photons fall on the receptive field of the ganglion cell during the critical duration, then the ganglion cell will fire. This means that a low luminance 'trickle' of photons can cause the firing of a single ganglion cell in much the same way as a single burst of photons (though downstream interpretation of this event will differ based on signals from neighbouring regions). Rods and cones have different critical durations (100ms and 15ms, respectively), possibly reflecting their optimal operating conditions (Stewart, 1972).

1.2 Age-related macular degeneration

1.2.1 Definition

Age-related macular degeneration is a visual disorder normally affecting older adults, and which results in partial or total loss of vision in the centre of the visual field. This loss of vision occurs as a result of damage to the macular part of the retina (the light-sensitive area in the posterior of the eye) (Hawkins, Bird, Klein, & West, 1999). As the macula is the most sensitive part of the retina, loss of function here can result in difficulties performing many habitual visual tasks (e.g. reading or recognising faces) (Geruschat, Fujiwara, & Wall Emerson, 2010; Midena, Degli Angeli, Blarzino, Valenti, & Segato, 1997; Pijnacker, Verstraten, Van Damme, Vandermeulen, & Steenbergen, 2011). Although central vision is disrupted in macular disease, many daily activities can still be carried out with the remaining peripheral vision (Boucart et al., 2008; Chung, 2011; Kalyanasundaram, 2008).

1.2.2 Incidence and prevalence

Age-related macular degeneration is a common visual disorder, with an estimated prevalence of 2.4% in the population aged 50+ (Owen, Jarrar, Wormald, Cook, Fletcher & Rudnicka, 2012). It accounts for half of blind and partial sight certifications in the UK (Bunce, Xing, & Wormald, 2010), affecting approximately 608,000 people as of 2010. This is expected to rise to 755,000 by 2020, due to increasing numbers of older people in the UK (Minassian, Reidy, Lightstone, & Desai, 2011). The numbers who experience debilitating sight loss as a result of macular degeneration are lower – approximately 223,000 in 2010, of which 145,000 were as a result of neovascular ("wet") macular degeneration. For adults over the age of 50, macular degeneration is the leading cause of sight loss (Kalyanasundaram, 2008).

1.2.3 Classification and pathogenesis

Macular degeneration broadly describes three separate disorders – neovascular (or 'exudative' / 'wet') macular disease; central geographic atrophy ('dry' macular disease) and juvenile macular disease (e.g. Stargardt's disease). Each of these disorders has an entirely different pathogenesis, although the perceptual outcome of the end-stage disorders is similar.

Stargardt's disease is a genetically transmitted disorder, with onset typically noticed before the age of 20 (Westerfeld & Mukai, 2008). Mutations in the *ABCR4* gene disrupt transportation of energy supplies to the photoreceptors of the macula, resulting in their premature death and subsequent loss of vision. As with other forms of macular disease, Stargardt's disease can ultimately result in significant loss of central vision (Miedziak, Perski, Andrews, & Donoso, 2000).

Neovascular (wet) macular disease accounts for 20% of cases overall, but 65% of cases of severe sight loss (Minassian et al., 2011). Vision loss occurs as a result of the growth of abnormal blood vessels in the choriocapillaris (a layer of capillaries in the vascular layer of the eye), which leads to blood and proteins leaking below the macula. The build-up of fluid and scar tissue causes

irreversible damage to the photoreceptors, with a consequent rapid decline in visual ability. This form can develop rapidly, with loss of central vision occurring within weeks or months (Calabrése et al., 2011).

Central geographic atrophy (dry macular degeneration) is the more common form, but accounts for a smaller number of cases of severe sight loss, partly due to its slow progression (Minassian et al., 2011). Vision loss occurs as a result of the atrophy of the retinal pigment epithelial layer, which normally provides nourishment (via the choriocapillaris) to the photoreceptors in the retina. These photoreceptors consequently die, resulting in a gradual loss of central vision (Tezel, Bora, & Kaplan, 2004).

A wide variety of risk factors have been identified across all types of macular disease. These include cigarette smoking (Seddon, Willett, Speizer, & Hankinson, 1996), cardiovascular risk factors (Snow & Seddon, 1999), sunlight exposure (Mitchell, Smith, & Wang, 1998; Taylor et al., 1992) and obesity (Seddon, Cote, Davis, & Rosner, 2003). However, by far the biggest risk factor is age itself (Chopdar, Chakravarthy, & Verma, 2003; Kalyanasundaram, 2008; Minassian et al., 2011; Owen et al., 2012; Owsley, 2011). Diet may also be implicated in macular disease, with several studies showing that dietary supplements may prevent the onset or slow the progression of the disorder (San Giovanni et al., 2008; Seddon et al., 1994).

1.2.4 Detection

Macular disease does not always develop in both eyes simultaneously, and patients do not always notice the loss of vision in a single eye (especially when the loss is gradual, as in dry macular degeneration). As a result of this, early detection can be quite difficult (Eichenbaum, 2012), but it is also essential to prevent further loss of vision (Loewenstein, 2007). Once the patient is aware that there is a problem, the Amsler grid (Amsler, 1953) is commonly used to identify the presence of distortions or scotomas (blind-spots) within the visual field (see figure 1.3). Since the loss of central vision dramatically limits visual acuity, letter acuity charts are also used to assess the patient's condition.

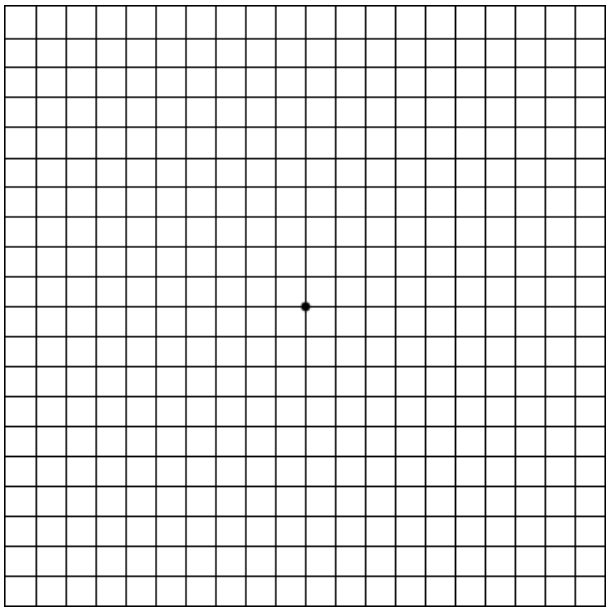

Figure 1.3: An Amsler grid. Fixating centrally, the patient reports any distortions or missing lines anywhere within the grid. This can alert the clinician to the presence, location and extent of damage to the retina.

For a more accurate view of the damaged retina, some form of fundus (the interior surface of the eye) photography can be used (figure 1.4 is an example of this type of photography). This form of diagnosis is becoming more common, and detection can now be automated in some cases (Güven, 2012). Alternatively, psychophysical methods such as perimetry have also been used. Perimetry has the advantage of giving a functional assessment of the patient's condition, and it is discussed at greater length in Chapter 2.

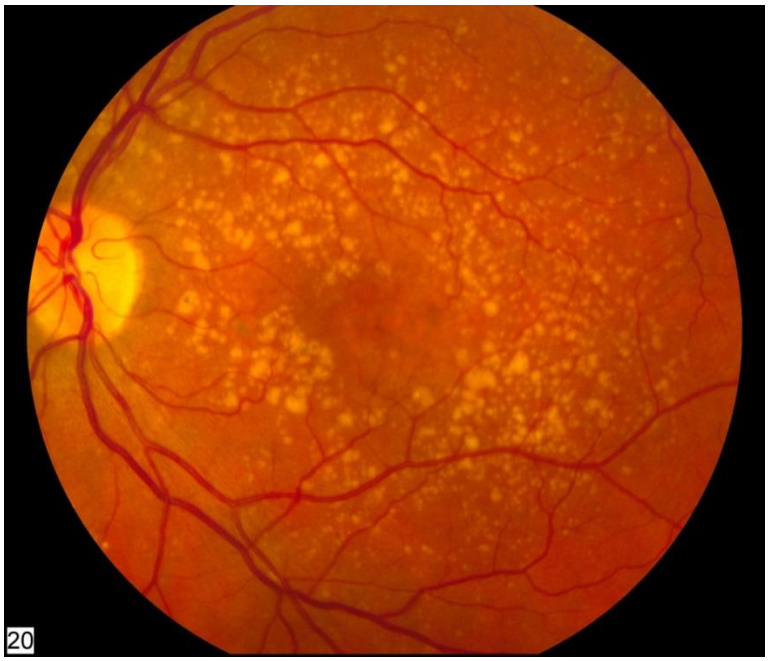

Figure 1.4: Image of the fundus showing localised atrophy of the retina due to dry macular degeneration (National Eye Institute of the NIH, n.d.).

1.2.5 Vision with macular disease

The macula is the most sensitive part of the retina, transmitting information that is processed to form our best levels of visual acuity, contrast discrimination and other perceptual abilities. Even minor damage to the macula can have severe behavioural consequences. Simple activities such as reading, recognising faces, navigation and driving become major obstacles (Brennan et al., 2011; Geruschat et al., 2010; McClure, Hart, Jackson, Stevenson, & Chakravarthy, 2000; Tejeria, Harper, Artes, & Dickinson, 2002). Indeed, the loss of reading and face-recognition abilities is widely reported as being the most significant loss to individuals with macular disease (Owsley, 2011). Reading in particular is the focus of a great deal of research into potential rehabilitation mechanisms, and is an area that is developed in the course of the current study.

Lacking foveal vision, individuals with macular disease generally resort to using their peripheral vision to perform some of these tasks, usually choosing to use the same discrete area of peripheral retina in place of the damaged

macula. An area of peripheral retina used for a defined percentage of viewing time is known as a preferred retinal locus (PRL) (Fletcher & Schuchard, 1997).

PRLs tend to occur naturally in the nasal visual field (Crossland, Culham, Kabanarou, & Rubin, 2005), though they can be found in other areas also (Crossland, Crabb, & Rubin, 2011; Markowitz, Reyes, & Shima, 2011). The shape of scotomas can be highly irregular, which has meant that some individuals have located PRLs for different tasks in different parts of their visual field. Indeed, in many cases more than one PRL can develop, and in this way individual PRLs can be used for separate tasks (Crossland et al., 2011).

Many individuals with macular disease tend to read with a PRL in the nasal visual field, which means that saccades have to be directed into the scotoma. This has been thought to decrease their accuracy, which may make reading more difficult. Some studies have shown that it is possible to train participants to relocate their PRLs to a more useful area of the peripheral visual field (Tarita-Nistor, Gonzalez, Markowitz, & Steinbach, 2009).

Compared to foveal vision, the periphery is hampered by reduced visual acuity (which makes most visual tasks more difficult), by significant crowding (Pelli et al., 2007) (see next section), and by decreased contrast sensitivity (Chung, Levi, & Li, 2006), even when viewing with a well-established PRL. Eccentric viewing also results in significant fixation instability (Gonzalez, Teichman, Lillakas, Markowitz, & Steinbach, 2006), particularly when the scotoma is greater than 20° in diameter (Whittaker, Budd, & Cummings, 1988).

All of these factors combine to reduce the usefulness of eccentric viewing to individuals with macular disease. Although magnifiers and other behavioural aids are an effective way of managing vision loss (Hooper, Jutai, Strong & Russell-Minda, 2008), they are not always acceptable to users. Specifically, many magnifying tools are unwieldy, or require extra assistance to set up and maintain. Given this, it is unsurprising that significant effort has been made to improve measures of reading speed, fixation stability and acuity through training and other means. These are dealt with later in this chapter.

1.2.6 Crowding

Crowding is a well-studied limiting factor in peripheral vision, and is highly relevant to the current study. It is generally defined as the negative influence of neighbouring visual features on perception of a target stimulus (Levi, 2008). Consequently it hampers perception of any related stimuli presented in the peripheral visual field (see figure 1.4 for examples), and is thus similar to masking.

Figure 1.4: Crowding affects perception of many stimulus features. In the photograph, it is easy to see the right-hand child in the road while fixating on the centre of the image, but less so the left-hand child. Similarly, in the right-hand image the targets above the fixation cross are easier to identify than those below.

Several features are characteristic of crowding (Whitney & Levi, 2011):

- It impairs discrimination, but spares detection. Therefore stimuli (which are generally perceived as high contrast, but unclear) can be detected but not identified.
- The strength of crowding is proportional to the eccentricity of the stimulus and inversely proportional to the spacing between target and flankers (Bouma, 1970). The critical spacing, at which no interference is perceived, is roughly 0.5 times the target's eccentricity.
- It is anisotropic. That is, radially positioned flankers are more disruptive than tangential ones (Toet & Levi, 1992) on the cardinal

axes. However, horizontal flankers tend to create a stronger crowding effect in the diagonal spaces between the cardinal axes (Whitney & Levi, 2011).

- Crowding is also asymmetric. Flankers that are more peripheral than the target exhibit a greater crowding effect than those more central than the target (Bouma, 1970).
- It depends on similarity. That is, it is tuned to individual features of the stimulus (e.g. faces of a particular orientation, letters, colours, orientations, etc.).
- It occurs dichoptically, even at the blind spot. That is, features presented in opposite eyes (but in neighbouring region of perceived space) can crowd each other. This implies a cortical site of action (after the site of binocular fusion).

Despite the similarities with masking, crowding is a separate phenomenon. In particular, the fact that detection is spared under crowding is a very important feature. Both overlap masking (when a target is overlaid on a masking pattern) and lateral masking (when overlapping or adjacent patches interfere) impair detection, and are thus dissimilar to crowding. Lateral masking is an interesting case, because it impairs detection when the mask is close to the target, but facilitates detection at wider spacing. Crowding is somewhat more similar to surround suppression (which occurs when the mask is located outside the receptive field(s) of the target neuron(s)), but surround suppression does not exhibit inward-outward anisotropy.

The precise mechanisms that cause crowding are unclear. As detection is spared, it seems likely that errors occur at a downstream site where simple features are integrated. It may thus be related to the increased receptive field sizes associated with areas of visual cortex that process peripheral vision.

In practical terms, the anisotropy and asymmetry of crowding have implications for the recovery of reading ability in macular disease. Words presented on the vertical meridian could experience less crowding than those

presented on the horizontal meridian (because different parts of the word are less likely to co-occur in the same crowding zone), leading to poorer performance on reading-based tasks.

In general, crowding (Chung, 2002; Pelli et al., 2007), fixation stability (Crossland, Culham, & Rubin, 2004) and scotoma size (Cummings, Whittaker, Watson, & Budd, 1985) all offer some predictive value with respect to maximum reading speed in individuals with macular disease. However, learning to identify crowded letters does not in itself improve reading speed (Chung, 2007), suggesting that the relationship between these factors is complex.

In the study by Crossland et al. (2004) fixation stability was found to account for 54% of the variation in reading speed. It is unclear what accounts for the the remaining variation, as fixation stability was not found to be related to scotoma size, visual acuity, or contrast sensitivity. However, in other studies larger scotomas (particularly those over 20° in diameter) were found to increase fixation instability, as well as decreasing reading speed (Whittaker, Budd & Cummings, 1988).

A further possibility is the involvement of changes in the visual span profile and the information transfer rate. Visual span profiles measure letter-recognition accuracy either side of the point of fixation. Their size is reduced in macular disease, and this is thought to impair reading speed (Legge, Mansfield & Chung, 2001). The time required for accurate letter-recognition is also impaired for individuals with macular disease (Cheong, Legge, Lawrence, Cheung & Ruff, 2007). It seems likely that quantification of a temporal aspect of peripheral reading speed is important in understanding the observed impairments. The concept of information transfer rate attempts to combine spatial (visual span profile) and temporal (letter identification speed) factors, and is also impaired in individuals with macular disease (Cheong, Legge, Lawrence, Cheung & Ruff, 2008). However, it is unclear if this has any additional explanatory power over its two constituent measures.

1.2.7 Treatment

A variety of treatments are currently available for neovascular macular disease, although the options for dry macular disease remain limited. Photodynamic therapy and laser photocoagulation have both been used extensively in the past, and are somewhat similar therapies. Laser photocoagulation uses a laser to either burn (and seal) individual leaking blood vessels in the retina (which can cause neo-vascular AMD), or to slow the growth of a wider network of blood vessels. Similarly, photodynamic therapy uses lasers to activate a medicine (pre-delivered to the blood stream) in retinal blood vessels. This medicine then causes clotting, blocking the abnormal blood vessels. Unfortunately both of these methods have limited success in preventing further deterioration of the macula and can also lead to further damage to the retina (Macular Photocoagulation Study Group, 1986; Wormald, Evans, Smeeth, & Henshaw, 2007).

Drugs which target VEGF (a protein implicated in the development of wet macular disease) have met with modest success in slowing and sometimes reversing the effects of the disorder (e.g. Brown et al., 2006; Dixon, Oliver, Olson, & Mandava, 2009; Gragoudas, Adamis, Cunningham, Feinsod, & Guyer, 2004). However, the long term safety of these therapies is as yet unproven, and patients' tolerance of the procedure varies. Other promising options include radiotherapy (Avila et al., 2011) and various gene therapies (Wickremasinghe et al., 2011), though both of these only target wet macular disease.

Despite such advances, treatments for dry macular degeneration remain limited. A recent pilot study demonstrated that administration of ciliary neurotrophic factor can slow the progression of the condition (Zhang et al., 2011), but pharmacological treatment has otherwise shown little promise. Developments in stem cell therapy research have indicated that this may be a viable future treatment option (MacLaren et al., 2006; Schwartz et al., 2012), but the use of stem cells may pose ethical issues in some societies.

Given this lack of current treatment options for dry macular disease, a large body of work in the behavioural sciences has focused on rehabilitation rather than treatment. The eye affected by dry macular disease cannot currently be repaired with any great reliability – therefore, it seems prudent to make efforts to maximise the usefulness of the remaining, healthy areas of retina. We cannot improve upon the basic physiology of the peripheral retina, so efforts in this field have focused on refining how we interpret the sensory output from this area. To do so, we must recruit the latent neural plasticity present in the adult brain. Previous research has indicated that this may be possible using perceptual learning protocols, which is the focus of the current study.

1.3 Neural plasticity

Neural plasticity refers to the capacity of the nervous system to adapt and change over time – to encode new information, and to allow some old information to be 'forgotten' (McClung & Nestler, 2008). In any learning system there must be a method of encoding new data. In the brain, where the basic units are neurons, it has long been thought that experience-dependent modification of the efficiency of synaptic connections between neurons would be an ideal basis for such a method. Hebb theorised that long-lasting, activity dependent changes in the efficacy of synaptic transmission are the basic process underlying learning (Hebb, 1949). These activity dependent changes are what we call synaptic plasticity, and it was first observed not long after Hebb proposed it.

The first form of synaptic plasticity to be observed was Long-Term Potentiation (henceforth LTP) (Bliss & Lomo, 1973). LTP has many features which make it a likely candidate for information storage – it can have a duration of up to several months, it is rapidly induced, strengthened by repetition, and occurs primarily in the hippocampus – a structure long associated with memory storage and retrieval (Kim & Yoon, 1998). It should

be noted that, as an artificial technique, LTP may be dissimilar in some way to the actual methods used for strengthening synaptic connections. It is, nevertheless, a useful experimental model for this natural process.

LTP or similar processes cannot be solely responsible for learning and memory within a neural network. If only increases in synaptic efficacy were possible, then synapses throughout the system would soon reach an undifferentiated ceiling of synaptic efficacy. Therefore a mechanism for depotentiating synapses is also necessary – long term depression (LTD). LTD has also been observed in the hippocampus, and both it and LTP have been found to be mediated by similar biological processes (Malenka & Bear, 2004).

Thus it seems that the firing propensity of different synapses can be quite different. These differences occur not just on the level of regular firing (as controlled by mechanisms of synaptic plasticity) but also on the level of their susceptibility to such mechanisms. This leads us to the crucial concept of metaplasticity.

Metaplasticity, as described by the Bienenstock-Cooper-Munro (BCM) theory, describes how the baseline plasticity of neurons might change over time (Bienenstock, Cooper, & Munro, 1982). Initially developed as a model of the development of neurons in the visual cortex, BCM theory is now thought to be relevant to all types of neural plasticity. According to this theory, the modification threshold, $Ø_m$, a measure of postsynaptic activity that determines in what direction a change in plasticity will occur (Kim & Yoon, 1998). If postsynaptic activity is below $Ø_m$ but above baseline, synaptic depression will occur. If it is above $Ø_m$ then synaptic potentiation will occur. The crucial part of the theory is that the value of $Ø_m$ can change as a time average of prior synaptic activity. It is thus bidirectional, and can account for the plasticity of synaptic plasticity, or metaplasticity.

Current theories thus account for experience dependent bidirectional changes in the firing probability of individual neurons and the circuits they comprise. This ability to alter patterns of activation is essential for any learning system –

allowing, for example, a reweighting of synapses to progressively enhance a signal deriving from a very faint or noisy stimulus. This has been observed to occur despite the fact that our visual systems have presumably been optimised both by our evolution as a species and each individual's lifetime of observing frequently encountered visual stimuli. This implies that the visual system retains the capacity for additional changes beyond those for which we have been optimised.

These types of changes could be extremely valuable to a population with macular disease. The peripheral retina (and associated cortex) has reduced sensory and processing power relative to central areas, so it is possible that processing of information from the periphery has a hard limit imposed by the machinery available to it. However, it is equally possible (and supported by observed improvements in peripheral vision) that processing of peripheral information is currently sub-optimal, leaving additional capacity for improvements. Reliable techniques for enhancement of peripheral visual abilities would constitute a novel, much needed form of rehabilitation for individuals with macular disease.

1.3.1 Development of the visual system

We know from a broad body of research that the visual system is amenable to plasticity-dependent change, and that this capacity for change varies throughout the lifespan. For example, new-born babies are hyperopic (long-sighted at birth), and this hyperopia naturally declines as the infant develops and learns (a process known as emmetropisation).

Significant early deficits in visual processes are often overcome during 'sensitive' periods in the development of the organism. A sensitive period is one in which experience has an unusually powerful effect on the brain (Knudsen, 2004). A familiar example is the way in which new-born animals imprint on their primary caregiver, forming a powerful (sometimes lifelong) association. During the visual system's sensitive periods, input of specific types of visual information is required in order for the visual system to

develop normally. For example, lid suture in a young animal will result in abnormalities in the distribution of ocular dominance columns in the visual cortex (Wiesel & Hubel, 1963). Deprivation of visual input occurring after this initial period has no permanent effect. However, it should not be construed that this sensitive period is sharply delineated in time – rather, it is a period of waxing and waning sensitivity. At its peak only a short period of deprivation is sufficient to cause interference, with increasingly longer deprivations required as the sensitive period wanes (Lewis & Maurer, 2005).

There are several different sensitive periods at play in the development of the visual system. Scotopic vision, visual acuity, contrast sensitivity and stereoscopic vision all develop at different time-points and on different time scales (Daw, 2003). However, even after these capacities have completed their development in the young organism, they can still be disrupted by subsequent deprivation (Lewis & Maurer, 2005).

It seems likely that during a sensitive period the neural plasticity of the brain is increased. Therefore, activity during this time will aid in the formation of stronger connections in the relevant neuronal circuits (Knudsen, 2004). An overall strengthening can be achieved by changes in the probability of neurotransmitter release, by the growth of new axonal and dendritic connections, but also by the elimination of synapses with a low probability of firing. These changes are all activity-driven, which is why deprivation has such a powerful effect during a sensitive period. Lacking the appropriate stimulation, neuronal circuits will remain under-stimulated, with a low probability of firing. They may even worsen due to synapse elimination (or 'synaptic pruning').

With such strong effects resulting from either normal development or deprivation in a sensitive period, it has often been assumed that significant changes were impossible in the developed brain. After these periods of increased plasticity it is certainly more difficult to induce changes, yet we now

know that training and everyday experience can make use of latent neural plasticity to promote behaviourally significant changes (Dinse, 2006).

1.3.2 Neural plasticity and age

Unlike the developing brain, it was once considered that the mature adult brain was 'rigid', incapable of the types of changes observed in the early stages of development. We have seen that working-age adults are capable of significant neural plasticity (Dinse, 2006; Mahncke, Bronstone, & Merzenich, 2006), but evidence for neural plasticity in older adults is weaker. This is crucial in the case of macular disease, as individuals with this condition tend to be above retirement age. Therefore it is particularly important that robust plasticity can be demonstrated in older adults. Even apart from macular disease, deficits in our sensory systems are far more common in later years, so methods for ameliorating these deficits would be extremely beneficial.

Some studies have begun to highlight age-related mechanisms that may affect or be affected by changes in neural plasticity. We know that declines in memory and processing speed are almost universal (Mahncke et al., 2006), with associated effects on other neural processes. This natural cognitive decline may be inevitable (should one live long enough) and is quite different to the pathological cognitive decline observed in conditions such as Parkinson's or Alzheimer's diseases. It is possible that a range of behavioural factors are at least partly responsible for natural cognitive decline. These include reduced activity levels (resulting from a more sedentary lifestyle, for example in retirement), increased perceptual noise, degraded neuromodulatory control (which regulates learning and plasticity) and negative learning processes (i.e. coping strategies that neglect and further weaken the systems they replace) (Mahncke et al., 2006). If these factors are the main culprits behind general cognitive decline, then they present a clear means to ameliorate this decline. Increasing activity levels and persevering with difficult tasks may counteract the reduced activity levels and negative

learning processes, respectively. Meanwhile, perceptual learning protocols, have been shown to reduce internal additive perceptual noise (Huang, Lu, & Zhou, 2009). We will discuss these techniques in greater detail shortly.

Supporting this research, imaging studies have shown that age-related decreases in task-related neural activity are quite common (Cabeza et al., 1997), particularly in areas associated with memory encoding and retrieval. However, other studies have shown that the opposite can also occur. Some tasks seem to produce an associated regional increase in neural activity. For example, top-down visual search tasks produce increased activity in the parietal and frontal lobes (Madden, 2007). It is thought that these types of patterns of increased activation (including activation in areas not strongly associated with the task) can form part of a compensatory response, allowing the brain to recruit additional resources to overcome age-related cognitive deficits (Persson & Nyberg, 2006). If this is a type of neural plasticity, it has limited success over the long term, where widespread patterns of low activation have been observed.

Nonetheless, it is now becoming clear that neural plasticity is much more widespread in the mature brain than had previously been thought, and that such reorganisation can have positive behavioural consequences (Dinse, 2006). While unable to restore an aged brain to its youthful state, it may still be possible to restore lost function by strengthening currently used neural circuits or recruiting alternative ones (potentially with corresponding alternative cognitive strategies).

In our case, age-related deficits of visual function have traditionally been tackled optically, using glasses or magnification devices. Given what we now know, it may make sense to also recruit the plasticity latent in the visual system to tackle this problem on a neural level.

1.4 Perceptual plasticity

Perceptual plasticity refers to the ability to alter perception through experience (Parkosadze, Otto, Malania, Kezeli, & Herzog, 2008), and has proven to be a useful behavioural model of neural plasticity in action. Research has shown that perceptual plasticity can result from adaptation to stimulus or environmental changes. It can occur at multiple timescales, from tens of milliseconds to minutes or even years, and can be observed at every level of the visual system, from photoreceptors to extrastriate cortex. Perceptual plasticity is of interest for two main reasons:

1. The neural mechanisms of learning and perception are revealed by studying perceptual plasticity in action;
2. Perceptual plasticity has been shown to have therapeutic applications in treating those with sensory deficits.

1.4.1 Perceptual learning

One well-studied case of perceptual plasticity is perceptual learning. This refers to relatively long-lasting changes in sensory function induced by experience of any kind, whether through training or through challenging natural sensory experience (Gibson, 1969; Sagi, 2011).

The types of training protocol used vary widely. However, they almost all focus on improving the ability to detect or discriminate relatively simple (at times fundamental) features of perception (Parkosadze et al., 2008). Generally speaking, training takes place over several days (sometimes weeks) with one training session each day. This is intended to eliminate potential fatigue from massed training, and also to encourage consolidation of the training.

The precise mechanisms of most forms of perceptual learning are currently unclear (Ahissar, Nahum, Nelken, & Hochstein, 2009), and training programmes must strike a fine balance between the specificity and the generalisation of their results. For example, training on bars of a certain orientation may not transfer to bars of a different orientation (Fahle, 2005)

and many other perceptual learning protocols also lead to specific improvements (Karni & Sagi, 1993; Polat & Sagi, 1994). Examples include contrast (Yu, Klein & Levi, 2004), spatial frequency (Sowden, Rose & Davies, 2002), motion direction (Saffell & Matthews, 2003) and background texture (Karni & Sagi, 1991).

If all observed improvements failed to generalise, then perceptual learning would have very little therapeutic value for disorders such as macular disease and amblyopia. However, other studies have shown complete transfer of learning between locations (Xiao et al, 2008), to the fellow eye (Li & Levi, 2004), and from a variety of tasks in amblyopic observers to Snellen acuity (Levi & Li, 2009).

Specificity is often thought to reflect the level of processing at which perceptual learning takes place (Sagi, 2011). Broadly speaking, the visual system can be characterised as having an initial, low-level analysis stage (that analyses basic stimulus features such as luminance differences, orientation, motion, etc.) and a higher level that uses these early representations to perform activities such as object recognition (Dosher & Lu, 1999). Training that has a highly specific outcome is often thought to cause changes in the early processing stage, where neurons code edges and orientations. More general training (such as for letter acuity or reading ability) is often thought to affect later cortical stages (Levi & Li, 2009), though this distinction is by no means a settled issue (Shibata, Sagi & Watanabe, 2014).

Such task-specific hypotheses are part of a wider discussion within the literature on perceptual learning. It is sometimes claimed that the adult visual system is plastic throughout the processing stream, from photoreceptors all the way up to extrastriate areas (Fine & Jacobs, 2002), and we have good reason to believe that perceptual learning is at least partly mediated by the primary sensory cortices in some way (Tsodyks & Gilbert, 2004). However, precisely where and how the changes wrought by perceptual learning take place is still a mystery. In particular the, the existence of generalisable

perceptual learning suggests that it may be a result of improved high-level task processing. There are two main theoretical stances on this issue.

In the classic view, the early representations of a given stimulus are modified, and these changes effect readout to higher cortical areas later in the processing stream (Schafer, Vasilaki, & Senn, 2007). The specificity of (some) observed perceptual learning suggests that learning occurs in areas where feature- or eye-specific information is processed (Priebe & Ferster, 2012). A potential issue with this theory is that such changes in early sensory cortex could also affect the processing of other (previously learned) stimuli that engage parts of the same cortical networks. Such interference does occur in a minority of cases (Seitz, Nanez, Holloway, Koyama, & Watanabe, 2005), but in general perceptual learning is highly task-specific, with no interference with other tasks (Fahle, 2005).

The alternative stance is that the basic representations remain unchanged, but that they are selectively reweighted on a task-specific basis (Petrov, Dosher, & Lu, 2005) by changes in higher-level decision-making areas (e.g. intra parietal sulcus, frontal eye fields, or anterior cingulate cortex) (Shibata et al, 2014). Other models have also supported this interpretation, which would suggest that perceptual learning-induced changes take place late in the processing stream (Petrov et al., 2005; Schafer et al., 2007). It is also supported by studies that demonstrate neural changes in cognitive areas that are associated with perceptual learning (Kahnt, Grueschow, Speck & Haynes, 2011).

Shibata's recent review (2014) attempts to clarify this dichotomy by proposing a multi-stage model of perceptual learning, where stimulus representations and task-related processing can be improved independently of each other. A similar proposal was made with reverse hierarchy theory (Ahissar et al, 2008) which proposes a dissociation between bottom-up stimulus processing and top-down perception. In these models (and dependent on the task), one aspect of perceptual learning can occur before the other (Karni & Sagi, 1993) –

for example, task-specific learning may precede transfer of learning to an associated task. This could explain some of the contrasting findings regarding specific and generalisable task improvements that have been observed

Although the bulk of the research in this area has focused on working-age adults, it is clear that perceptual learning is a prominent feature of the visual system throughout the lifespan (Ferchmin & Eterović, 1986; Mirmiran, van Someren, & Swaab, 1996). For example, children pass through a 'critical period' in which experience has a particularly strong effect (Knudsen, 2004), and they are generally capable of significant perceptual plasticity, which has been recruited for therapeutic purposes (Astle, 2010; Hussain, Webb, Astle, & McGraw, 2012; Li, Young, Hoenig, & Levi, 2005; Mintz-Hittner & Fernandez, 2000).

In the adult visual system, perceptual learning can lead to improvements in a wide variety of abilities including positional discrimination (Li et al., 2005), contrast detection (Huang et al., 2009), orientation and motion discrimination (Ball & Sekuler, 1986), peripheral reading ability (Chung, 2011; Yu, Cheung, Legge, & Chung, 2010), and can also lead to reductions in equivalent input noise (Li & Levi, 2004). Maintenance of these improvements has been observed at multiple time-points up to 2 years after training has ended (Karni & Sagi, 1993; Zhou et al., 2006).

A crucial issue which makes research with older adults more difficult is that increasing age sees a distinct worsening in our general perceptual abilities. In the visual system, this manifests as a worsening in visual acuity, contrast sensitivity, peripheral vision, motion processing, colour vision and temporal acuity (Jackson & Owsley, 2003), as well as orientation / direction selectivity (Leventhal, Wang, Pu, Zhou, & Ma, 2003; Schmolesky, Wang, Pu, & Leventhal, 2000) and visual search ability (Madden, 2007). Some of these deficits are attributable to optical factors (e.g. hardening of the lens) but others are a result of neural reorganisation or decline in the ageing brain (Blake, Rizzo, & McEvoy, 2008).

This decline in perceptual abilities appears to be at least partially amenable to treatment. The pattern of results is somewhat varied - for example, in visual search tasks young adults do not improve as much as older adults (Rogers & Fisk, 1991). In motion-direction tasks, young and old adults improve equally, but it takes longer for the older adults' thresholds to reach asymptotic levels (Ball & Sekuler, 1986).

These studies indicate that older adults are capable of visual perceptual learning, although their improvements are often of a lesser magnitude (Yu et al., 2010). More training sessions (Richards, Bennett, & Sekuler, 2006) or grouping the training sessions within a single day (Fahle & Daum, 1997) could help to improve overall performance and permit the transfer of improvements to other tasks. With training, it may thus be possible to induce improvements in the visual perception of older adults.

The effectiveness of perceptual learning in adults demonstrates that significant improvements in adult visual abilities are achievable. Evidence from research into amblyopia further suggests that perceptual learning can at least partly ameliorate deficits accrued during sensitive periods. It is to this issue that we now turn our attention.

1.4.2 The case of amblyopia

Amblyopia (commonly known as 'lazy eye') is a developmental visual disorder, usually affecting one eye. The primary deficits associated with amblyopia include reduced visual acuity and contrast sensitivity (Levi, Song, & Pelli, 2007), reduced positional acuity (Barrett, Morrill, & Whitaker, 2000) and increased crowding (Li et al., 2005). Thus amblyopic vision is at least superficially similar to peripheral vision. These deficits are observed despite optical correction and even in the absence of other ocular pathologies, indicating a neural basis for the disorder. As a result of these similarities, amelioration of the symptoms of amblyopia may prove to be a useful model in the development of a rehabilitation programme in macular disease. However, comparisons should be treated with caution. Amblyopia is a cortical

disorder, thus necessarily different to AMD (a disorder of the retina). Nonetheless, we believe that the comparison is useful in principle.

Traditionally, amblyopia has been treated with patching in early childhood. Early intervention has generally been considered to be crucial, as visual improvements are more easily induced during the relevant sensitive periods. Treatment generally involves occluding the dominant eye, thus encouraging a strengthening of the visual input from the amblyopic eye (Mintz-Hittner & Fernandez, 2000). Clearly this technique cannot be applied to individuals with macular disease. Even the development of a stable PRL, which similarly compels the use of a previously unused area of retina (and corresponding visual pathway), does not produce improvements in visual acuity on the same order as patching in amblyopia.

However, perceptual learning has also been used to attempt treatment of amblyopes (for example Astle, 2010; Levi & Li, 2009), and maintenance of these improvements has been observed up to 12 months after training has ended (Zhou et al., 2006).

Thus it seems that perceptual learning can produce improvements in some forms of visual disorders. Since those parts of the visual system that encode foveal vision can be improved upon, it seems possible that improvements can also be made in peripheral vision (with the obvious caveat that the underlying 'hardware' of the peripheral retina is simply not as refined as that of the amblyopic fovea). However, with our focus on age-related macular degeneration, it is important to also understand the effects of ageing on perceptual learning.

1.4.3 Visual perceptual learning and age

We have seen previously that reorganisation can take place in the mature brain (by which we generally mean adults above retirement age, or 65). We will now examine some of the changes that have been observed in the mature visual system using perceptual learning protocols.

Work in this area has been on-going for some time. Some studies have shown no effect of ageing on task performance. For example, age does not seem to affect initial or post-training performance on a dichoptic masking paradigm (Hertzog, Williams, & Walsh, 1976). On the other hand, clear effects of age have been observed on tasks such as detection of the direction of motion (Ball & Sekuler, 1986). This type of task is particularly well-suited to research on ageing, as it is relatively insensitive to acuity deficits. Although older observers have a poorer initial threshold, their improvement due to training is identical to that of younger observers. This indicates clearly that the mature perceptual system is capable of significant plasticity.

Mature adults can also improve performance on many low-level tasks such as visual acuity & contrast detection/discrimination (Polat, Schor, Tong, Zomet, Lev, Yehezkel, Sterkin & Levi, 2012), motion discrimination (Bower, Watanabe & Andersen, 2013), letter discrimination (Andersen, Ni, Bower & Watanabe, 2010), visual search (Ratcliff, Thapar, & McKoon, 2006), and texture discrimination (Ni, Watanabe, & Andersen, 2007). As we have seen, the pattern of results can be varied – for example, young adults improving less than older adults on a visual search tasks (Rogers & Fisk, 1991) or both groups improving equally on a motion direction task (Ball & Sekuler, 1986).

Some interesting theories have been posited regarding the locus of these types of improvements. It is thought that performance on these tasks is limited in older adults in two ways. The quality of the sensory representation is reduced in old age, with poorer visual acuity, increased noise, etc (Jackson & Owsley, 2003). Cognitive biases can also come into play, which is of particular importance in these types of research. It has been known for some time that older observers can be more cautious, and overly-reluctant to indicate changes on same/different forced choice tasks (Rees & Botwinick, 1971). In contrast to this, younger observers normally have lower response criteria, and are more willing to change their response strategies during a task (Ratcliff et al., 2006). Note that these biases are generally only true at the

beginning of a task – after a sufficient number of trials, older adults are also capable of changing their response biases.

It is thus clear that older adults are capable of significant visual perceptual learning (though perhaps not so much as younger adults). In peripheral vision, older adults are capable of improving several measures linked to reading ability, at 10° in the upper and lower periphery (Yu et al., 2010). Among these are visual span (the number of letters that can be discriminated in a single fixation – without further eye movements) and rapid serial visual processing (a technique where words are presented sequentially in the same position). However, the training effects were weaker in older than in younger adults, and showed a reduced transfer to alternative print sizes or locations. It may be possible to ameliorate some of these deficits. For example, increasing the number of training sessions (Richards et al., 2006) or grouping the training sessions within a single day (Fahle & Daum, 1997) has been shown to improve overall performance and transfer of performance on some tasks.

Despite these caveats, it seems clear that training can produce positive improvements in the visual perception of older adults, which may be of great value in the treatment of age-related visual disorders such as macular disease.

1.4.4 Perceptual learning and macular disease

The characteristic deficits of peripheral vision include many of the same visual abilities that we know to be amenable to improvement through perceptual learning. By harnessing the latent perceptual plasticity in the mature visual system it may be possible to generate an area of improved vision in the peripheral visual field – similar to, but more sensitive than, a naturally occurring PRL.

Improvements in various perceptual tasks have been shown to be possible in individuals with macular disease. Recent reviews, however, have demonstrated mixed effects for different types of training protocol (Pijnacker et al., 2011).

Several studies have shown that training eccentric viewing (learning to use another location for reading) leads to improvements in reading ability at the trained location (Gustafsson & Inde, 2004; Frennesson, Jakobsson & Nilsson, 1995; Nilsson, Frennesson & Nilsson, 2003). This is a crucial ability for those people with central vision loss, who are required to use eccentric viewing for all visual tasks. The average improvement in reading speed from these studies was 60-80 words per minute (wpm). However, they all used optical devices in addition to the provision of training. It is thus likely that the observed improvements are only partially attributable to perceptual learning.

Several studies have also used perceptual learning protocols to directly train reading ability, with mixed results. Chung (2011) found that participants with age-related macular disease improved on an RSVP sentence reading task, as did a group with juvenile macular disease in a separate study (Nguyen, Stockum, Hahn, & Trauzettel-Klosinski, 2011). Conversely, a separate study (Seiple, Grant, & Szlyk, 2011) failed to observe any such improvement on a group with age-related macular disease who underwent RSVP training. A more recent study (Tarita-Nistor, Brent, Steinbach, Markowitz & Gonzalez, 2014) trained a group with central vision loss binocularly on a serial word-reading task, presented at the participant's reading acuity limit. This led to a significant improvement in the stimulus duration required to correctly identify the words presented, and learning appeared to generalise to reading acuity and maximum reading speed.

The latter finding is important, as reading ability is one of the key skills that is most missed by individuals with macular disease (Crossland, Gould, Helman, Feely & Rubin, 2007). Prior to these recent studies, a great deal of research was dedicated to inducing learned improvements in proxies for normal reading ability in the peripheral vision of normally sighted individuals, as well as those with macular disease. These proxies include tasks such as RSVP (Rapid Serial Visual Presentation) reading, trigram (three letter) word-recognition, word/non-word tasks, visual span profiles, and letter recognition. Normally-sighted individuals are often used in place of individuals with

macular disease in these tasks, due to the difficulties in recruiting and providing regular training to a clinical population. Although we can train improvements in normal peripheral vision, we must bear in mind that the normal peripheral retina is not necessarily a like-for-like match to that of an individual with macular disease. Similarly, we must question the external validity of the types of tasks used in these perceptual learning studies. The precise mechanics of many forms of perceptual learning are still unclear (Ahissar et al., 2009), and training programmes must strike a fine balance between the specificity and the generalisation of their results.

Crucially (for the purposes of rehabilitation) training on simple tasks such as position discrimination, contrast detection and Vernier acuity appears to transfer to Snellen (letter) acuity (Zhou et al., 2006). However, reading ability involves a great deal more than letter acuity. Since it appears to be a good predictor of general visual ability (McClure, Hart, Jackson, Stevenson & Chakravarthy, 2000) and quality of life (Hazel &Latham, 2000) we intend to incorporate it as a significant part of our study.

1.5 Thesis plan

Perceptual learning is a valuable tool, which can induce improvements in a wide variety of perceptual tasks and corresponding abilities. Over the course of the current study, we aim to use perceptual learning and psychophysical techniques to investigate the feasibility of developing a training programme that can induce behaviourally significant improvements in the vision of individuals with macular disease.

To achieve this goal we first need to determine the elements that should comprise such a programme. With that in mind, we plan to investigate the relative merits of training individuals of all ages on one of three key tasks – word recognition, contrast sensitivity with a Landolt C, and positional discrimination (a bisection task). From Zhou et al. (2006) we know that improvements in contrast detection and position discrimination can

generalise to Snellen acuity. We hypothesised that this might further generalised to improvements in word recognition, our initial proxy for reading ability. The word recognition task itself was chosen as a higher level task more closely linked to normal reading behaviour.

As part of this study, we also investigate the effect of age on learning in these tasks. We know from previous research that age can lead to changes in aspects of cognition and neural activity. For example, in section 1.3.2 we described declines in memory and processing speed (Mahncke et al., 2006), decreases in some task-related neural activity (Cabeza et al., 1997), but also increases in parietal/frontal activity for other tasks (Madden, 2007). It is possible that these types of changes may associated with an age-dependent effect of age on learning. If this has an observable negative impact, we will seek to determine what steps are necessary to ameliorate any deficits.

These two initial components to the study will help us to determine the form of a potential rehabilitation programme for individuals with macular disease. However, two key issues that can affect peripheral reading ability remain to be assessed. First, it is important that we understand the effect of crowding in our target population, since almost all natural reading tasks are highly crowded. Given that crowding is known to be a potent 'bottleneck' for reading ability (Levi, 2008), and that the perceptual abilities of the ageing brain are limited in many other ways, it seems plausible that crowding might be exacerbated in older individuals. Therefore we planned a simple study to determine precise crowding ratios for a broad cross-section of ages. Should crowding prove to be an extra burden in the visual system of older adults, we would need to consider training programmes that reduce crowding (Chung, 2007).

The second issue that might adversely affect any rehabilitation programme is fixation instability. Individuals with macular disease have poorer fixation stability than normally sighted individuals (Bellman, Feely, Crossland, Kabanarou, & Rubin, 2004; Macedo, Crossland, & Rubin, 2011). While this

does not affect crowded or uncrowded visual acuity, an inability to fixate could lessen or eliminate any potential gains from our learning task. Instability has already been demonstrated to significantly impair reading rate (Falkenberg, Rubin, & Bex, 2007), so it is extremely important that we understand how and to what extent the instability typical of macular disease can affect the perception and learning of letter-based stimuli.

Finally, we aim to implement a small study (based on the results of the first parts of this programme) to determine the potential for training improvements in reading ability in a sample with macular disease. As a part of this study, we aim to use a controlled reading-based task as a measure of external validity - improvements in the lab alone, while theoretically interesting, do not necessarily have any therapeutic application. Should we observe any promising improvements in ability, this data will be of use both to future research programmes and the rehabilitation of the growing number of individuals with macular disease.

Chapter 2: General methods

2.1 Observers

Participants were recruited from within the University of Nottingham; via a local Macular Disease support group; and from the University of the Third Age (U3A). All subjects were optically corrected for the appropriate viewing distance. Informed consent was obtained from the subjects after explanation of the nature of the study. The experimental procedures adhered to the tenets of the then current Declaration of Helsinki (v6, 2008) and were approved by a local ethics committee at the School of Psychology, The University of Nottingham.

Data was collected from 121 individuals with normal vision, and from 5 individuals with age-related macular disease. The age of observers with healthy vision ranged from 17 to 90 years, with a mean of 42 and a standard deviation of 21. The observers with macular disease ranged from 67 to 81 years, with a mean of 76 and a standard deviation of 6.

All observers underwent a variety of screening examinations prior to the start of their testing. Refractive error and corrected visual acuity were assessed, and all participants were screened for cognitive impairments using the Mini Mental State examination (MMS) (Folstein, Folstein, & McHugh, 1975).

Observers were fully optically corrected prior to testing. Testing was carried out monocularly, with the fellow eye occluded by an opaque lens. The eye used was chosen randomly for each normally-sighted observer. The eye chosen for macular observers was based on data obtained from the Amsler grid (Amsler, 1953) and perimetry testing using the Humphrey Visual Field Analyser. For computer-based tasks, the observers' heads were fixed in the viewing position using a chin rest.

2.1.1 Inclusion and exclusion criteria

For inclusion in the study, normally sighted observers had to present with no serious ocular pathology, and with visual deficits capable of being corrected to normal. 9 normally sighted participants were excluded from the study – 5 because they were unable to maintain fixation, 2 due to illness, and 2 for personal reasons.

Observers with macular disease had to present with a diagnosis of macular disease (wet or dry) in one or both eyes. The affected eye had to show evidence of a central scotoma that significantly affected both visual acuity (as recorded on the Bailey-Lovey LogMAR test (Bailey & Lovie, 1976)) and contrast sensitivity in central vision (as measured using the Humphrey Visual Field Analyser).

All observers were screened for cognitive impairments using the Mini Mental State Examination. For normally sighted observers, the mean MMSE score was 29.7 out of 30 (range 28 to 30). For observers with macular disease, the mean score was 29.2 (range of 27 to 30). This task has a cut-off point at 27/30. No observers scored below the cut-off point on this test.

2.2 Apparatus

Stimuli were generated on a gamma-corrected Personal Computer (PC) using custom software written in Python (version 2.4) (Peirce, 2007), and displayed on a 14-inch Cathode Ray Tube (CRT) monitor (Belinea 108035; [Maxdata, Marl, Germany]). This ran at a resolution of 1024x768, with an update rate of 85 Hz. The contrast resolution was boosted from 8 to 14-bit using a digital-to-analogue Bits++ box (that is, from 256 to 16,384 grey levels) (Cambridge Research Systems Ltd.). Except where otherwise stated, all stimuli were displayed on a mean-luminance grey background (90cd/m^2). The monitor was the only source of the light in the test-room.

2.2.1 Monitor calibration

In order to precisely control the stimuli in these tests, the characteristics of the monitor had to be understood and controlled. Many CRT monitors have a non-linear relationship between the input voltage to the monitor and the output (displayed) luminance. Correcting this non-linearity is known as "gamma correction", and allows stimuli to be displayed with precisely controlled increments in their luminance values.

Output luminance was measured for a range of 22 input luminances using a Minolta CS-110 photometer (Konica Minolta, Canada), which outputs a time-averaged luminance value. The output luminances were graphed against their input luminances, and the resulting data-points fitted with an equation of the form:

$$y = ax^c + b \tag{2.1}$$

This is the standard equation of a line, with the addition of c, a modifying exponent that introduces non-linearity to the standard form. The constants a and b are free to vary; y represents the output luminance; and x the requested input luminance. From this equation, we can see that when x and y have a linear relationship, the value of c is equal to 1.

The value of c was found to be 2.004. This value was used to create an inverse look-up table in Python, which corrected the non-linearity between input and output values. As confirmation that the non-linearity had been corrected, output luminances were recorded a second time to ensure that the relationship had become linear (see figure 2.1). The r^2 value (a measure of goodness of fit) for the regression line fitted to the post-correction data is equal to 0.99.

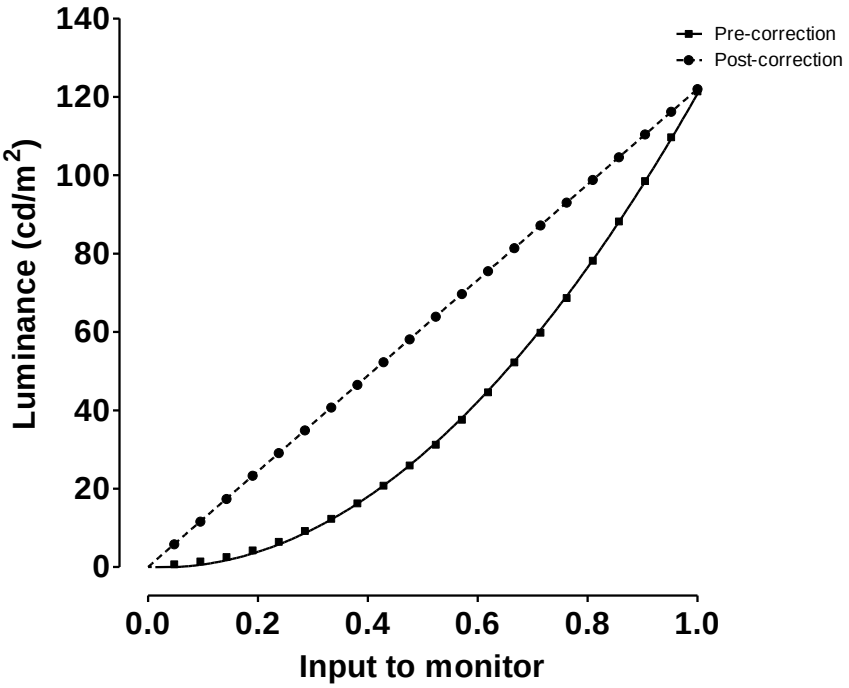

Figure 2.1 Gamma functions for the Belinea monitor before and after gamma correction. The curve through the pre-correction data is the best fit of equation 2.1.

2.2.2 Calculating working distance

All monitors display images using pixels of a discrete size. At close viewing distances pixelation and aliasing (distortion occurring when the displayed image is different to the original signal, usually due to issues of insufficient resolution) of the image become inevitable. In order to avoid this, a working distance was required that prevent the viewing of individual pixels, allowing the perception of a continuous image. However, this study is also constrained by the requirement for large viewing angles on screen. As described in a later section, a viewing angle of up to 13° is required between the centre of the screen and the target stimulus.

The monitor's display is 0.377m wide, corresponding to 1024 pixels. Therefore, each pixel takes up 3.68×10^{-4}m. The display is 768 pixels high, half of which is 384 pixels (equivalent to 0.141m). Using a viewing distance of 0.57m, the maximum viewing angle then becomes:

$$Tan^{-1}(0.141/0.57) = 13.7° \quad (2.2)$$

We can perform a similar calculation based on the pixel size and viewing distance to calculate the size (in degrees of visual angle) taken up by a single pixel.

$$Tan^{-1}(0.000368/0.57) = 2.2' \quad (2.3)$$

Observers with normal vision are capable of resolving details of 1 min of arc, so this viewing distance means that some distortion of the perceived image would still be possible using central vision. However, when using peripheral vision (at 10° eccentricity in the upper visual field) during piloting, no pixelation or aliasing were observed in the displayed images.

2.2.3 Macular observers

Perimetry testing for macular observers was carried out using a standard black-on-white Amsler grid (figure 1.1) and a Humphrey visual field analyser (Carl Zeiss Ltd, UK).

The Amsler grid can be used to rapidly identify the location and extent of any defects in the participant's visual field. Fixating on the grid, participants report any aberrations or missing parts of the grid, and this is recorded by the experimenter.

The Humphrey visual field analyser is designed to detect defects in visual sensitivity at a wide range of eccentricities. It works by displaying flashes of light around a bowl set into the machine, with a fixed background light level. A full threshold test (which makes very few assumptions about the participant's visual abilities) was used to determine the sensitivity of the retina at each point of interest in the visual field. After screening our participants for defects within a 10° radius of fixation, we opted for the Central 10-2 protocol, which makes detailed measurements of the central 20° (diameter) of the participant's visual field.

2.3 Stimuli

2.3.1 Lettering

All of the letter-based tasks in this study used upper case letters in the Arial font as their stimuli. Individual tasks used various subsets of the full alphabet, and will be described with the corresponding protocol. Like many fonts, Arial has particular characteristics that can cause problems in letter identification studies. For example, the letter C is easily mistaken for an O; so much so that it has been recommended that either response should be recorded as a correct response (Elliott, Whitaker, & Bonette, 1990).

2.3.2 Landolt C's

Like the Sloan font, the Landolt C is an optotype (a standardized character or symbol used for testing various aspects of vision). It consists of a ring with a gap, where the stroke width is equal to the gap width (and both are $1/5^{th}$ of the diameter of the ring). The gap can be oriented in any direction (generally cardinal directions), and this optotype thus resembles a letter 'C' rotated to varying degrees (figure 2.2). When used in vision testing, the observer's task is to identify the location of the gap. This has several advantages over acuity testing with letters. When only the cardinal axes are used, there are only four possible responses for an observer to make, which makes responding with the keyboard simpler. Each position is also equally discriminable – this certainly cannot be said of letters, where we have seen that confusion is highly likely between certain letters.

When using Landolt C's, the size of the target is usually varied until the orientation of the gap is no longer discriminable, giving a measure of the observer's visual acuity. In our study we instead vary the contrast of the C until the orientation of the gap is no longer discriminable. The contrast of the C was defined as Michelson Contrast (WC):

$$MC = (L_T - L_P) / (L_T + L_P), \quad (2.4)$$

where L_T represents the luminance of the target C, and L_P represents the luminance of the background.

In this case the minimum perceivable value can be taken as a measure of the observer's contrast sensitivity.

Figure 2.2 Landolt C's of varying sizes and orientations

2.3.3 Gaussian blobs

The prosaically named 'Gaussian blobs' were used in a bisection acuity task. These are symmetrical circular targets with a Gaussian luminance profile (figure 2.3). Unlike letter acuity and contrast sensitivity tasks, many aspects of positional acuity tasks are thought to be unaffected by the types of optical image degradation commonly found in aged eyes (Latham & Barrett, 1998). However, positional acuity in general and three-dot bisection (as used in this study) in particular are known to be significantly impaired in peripheral vision relative to the fovea (Klein & Levi, 1987; Wilson, 1991; Yap, Levi, & Klein, 1987). Improvements in positional acuity could thus be useful for older adults with central vision loss, particularly as this may also generalise to improvements in Snellen acuity (Zhou et al, 2006).

Although most assessments of peripheral vision have used stimuli with clearly defined edges, here we elected to use the prosaically named 'Gaussian blobs'. These are symmetrical circular targets with a Gaussian luminance profile, which serves to increase the difficulty of the positional task. In early piloting, circular patches with clearly defined edges were used, but participants were quickly able to achieve the minimum possible thresholds under these conditions. Therefore, Gaussian blobs (whose edges are indistinct) were used to make the task more difficult.

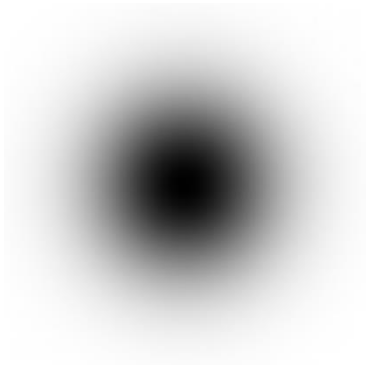

Figure 2.3 A symmetrical, circular Gaussian blob

2.4 Psychophysical methods

This project is primarily concerned with studying improvements in the perceptual abilities of the peripheral vision of older adults. The study of the relationship between stimuli and sensations/perceptions is known as psychophysics.

Psychophysics measures the relationship between physical stimuli (light, heat, pressure, sounds) and psychological sensations. Many of the methods associated with this field are used to measure the minimum amount of physical energy required to induce a sensation (i.e. to detect the stimulus) or the minimum difference between two stimuli required to make them discriminable. The principles presumed to govern the relationship between stimulus and percept were originally studied in the 19th century (Fechner, 1860). Two key concepts are relevant to the current study: Thresholds, and adaptive staircases.

2.4.1 Thresholds

As noted above, there are two primary measurements that are commonly used with psychophysical techniques. These are the ability to detect a stimulus, and the ability to discriminate between different stimuli. We have used both of these techniques in this study.

The minimum energy level at which a stimulus can be detected is defined as the absolute threshold of the observer (for that specific task, at that point

time). More practically, this can be characterised as the lowest level of a stimulus that can be detected by a participant on a defined proportion of trials (e.g. 100% of trials, or more commonly a lower proportion to allow for the fact that observers are unlikely to detect the stimulus on every trial).

The absolute threshold can be contrasted with the "just noticeable difference" (jnd). This is the smallest detectable difference between two levels of a stimulus. As with the absolute threshold, this is a statistical quantity – the difference that an observer can detect on a defined proportion of trials.

2.4.2 Adaptive staircase procedure

A variety of techniques have been employed to measure thresholds. In these experiments, adaptive staircases were used. In this method, the stimulus is initially presented at an easily detectable (or discriminable) level, and then gradually altered as a function of the observer's responses. The majority of the experiments reported here use a 3-up, 1-down staircase, which is known to converge on a performance level of approximately 79% correct responses (Levitt, 1971). That is, the stimulus intensity (or difference) is decreased for every three correct responses (the task becomes harder). Conversely, the intensity increases for any incorrect response (the task becomes easier).

When the initial intensity has been set to a suitable value, a procedure of this form should result in a staircase similar to that shown in figure 2.4. In this case, the duration of the stimulus decreases while the observer continues to make correct responses, before increasing after the first error on trial 7. The advantage of this method is that responses quickly converge on the (presumed) threshold of the observer on that task, and in most cases the majority of the responses are around this level. This makes it quite efficient, in comparison to other methods of threshold-estimation.

However, thresholds often fail to converge at a given level of stimulus intensity. Staircases that failed to converge in this manner were evaluated on a case-by-case basis. This was a particular problem in the first two training sessions on the word-recognition tasks, where participants were arbitrarily

limited by a ceiling-effect imposed by the task design. In these cases we included staircases where more than 50% of trials were at a level of stimulus intensity below the arbitrary ceiling, which was only possible when participants were correct on more than 50% of trials.

Staircases later in the training phase were evaluated by eye, and rejected if the final six reversals did not appear to be converging. However, this was rarely a problem after the first two days of training.

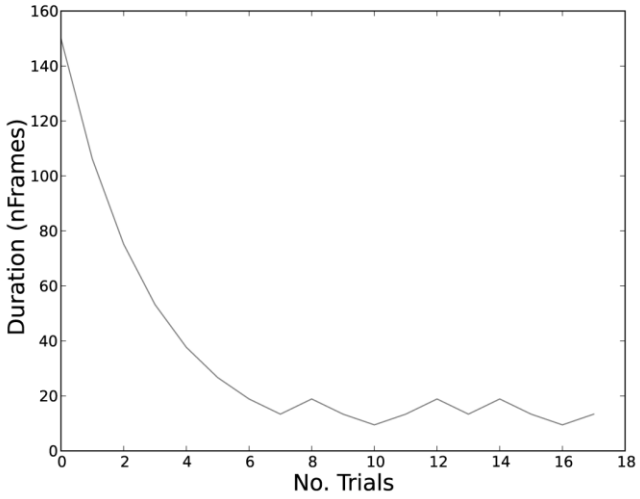

Figure 2.4 Sample staircase for a single measure on the RSVP task. The duration of the stimulus onscreen was gradually reduced until the participant began to make errors, at which time the duration was increased. A series of these decreases and increases in duration comprise the staircase, from which an estimate of the participant's threshold can be made.

2.5 Test procedures

2.5.1 Three-dot bisection

This task was designed to match the spatial configuration and the axes of judgement of the contrast task (see section 2.5.2). Three Gaussian blobs were presented in a row – alternating between a horizontal and a vertical condition (figure 2.5). The stimuli used in each configuration were identical apart from the position of the Gaussian blobs.

Each row of blobs was centred at 10° above fixation. The outer two blobs were each 3.75° from this centre point, placing them in the same spatial location as the outer C's in the contrast task, and the outer letters in the reading task. The standard deviations (sigma) of the inner and outer Gaussian blobs were 0.58° and 1.73°, respectively. Each set of Gaussians was displayed for 900 ms.

In this task, the smaller target blob is initially presented at a distance of 0.45° from the centre of the axis formed by the two larger blobs. Participants were required to determine which larger blob it was closer to, using the arrow keys on the keyboard. This task is thus a two-alternative forced choice task. A tone sounded to indicate incorrect responses. As accuracy increased, the distance between the target and the centre-point was designed to reduce in step-sizes of 0.02° (1.2 arc min). This value is less than the size of a pixel (2.2 arc min), meaning that the target did not move after every set of three trials (it would move on average every 1.8 sets of trials). Though it is likely that this slowed down participants' transition from high to low thresholds, this issue did not appear to affect the shape of the staircases or their convergence.

The target was randomly assigned to be either side of the centre of the axis on each presentation. The vertical and horizontal conditions alternated in sequence. A predictable temporal pattern of this kind is essential in order to maximize learning (Kuai, Zhang, Klein, Levi, & Yu, 2005). The position of the target was calculated and recorded separately in each of the conditions, and the program terminated after 8 reversals. This staircase operated on a 3-up, 1-down rule, targeting the 79% correct point on the psychometric function.

Participants were instructed to use the arrow keys on the keyboard to indicate the direction of the target (outer) Gaussian blob on each trial. They were monitored by the experimenter throughout their first five sessions to ensure that they were responding correctly.

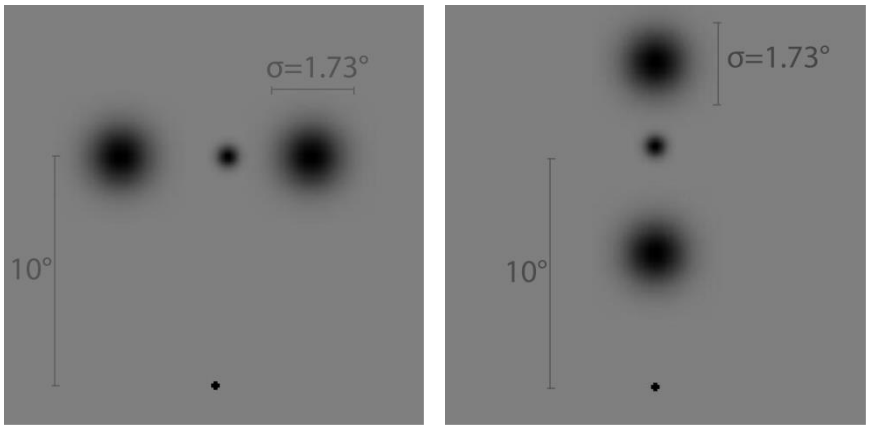

Figure 2.5 Sample trials on the position task. Observers determined which outside Gaussian blob the central, smaller blob was closer to. The distance between the smaller Gaussian blob and the centre of the array varied on an adaptive 3-up, 1-down staircase.

2.5.2 Letter contrast

This task was designed to match the spatial position and axes of judgement of the bisection acuity task (see section 2.5.1). The stimuli for the contrast task are shown in figure 2.6. Participants fixated on the central dot, and an array of Landolt C's was presented in the upper visual field. The central C was centred at 10° above fixation. Each of the C's was comprised of an outer circle subtending an angle of 2.5° to the observer, and an inner circle of 1.5°. The gap in each C was 0.5°, and the spacing between Cs was 3.75°. This placed the outer Cs on the horizontal axis in the same region of visual space as the crowding outer letters in the RSVP task, and the outer Gaussian blobs in the bisection acuity task. The starting level was 0.45 Michelson contrast, and each array of Cs was presented for 900ms.

All of the C's were rotated randomly on each trial, but the central C was restricted to cardinal orientations (i.e. the gap was at the top, bottom, left or right). The task was to judge the orientation of the C, with difficulty manipulated by changes in the contrast of the C's. Observers used the arrow keys on the keyboard to code their responses. A tone was sounded to indicate errors. The staircase operated on a 3-up, 1-down rule, targeting the 79%

correct point on the psychometric function. The step size used was log 0.03. The program terminated after 8 reversals.

Participants were instructed to use the arrow keys on the keyboard to indicate the orientation of the gap in the middle Landolt C. They were monitored by the experimenter throughout their first five sessions to ensure that they were responding correctly.

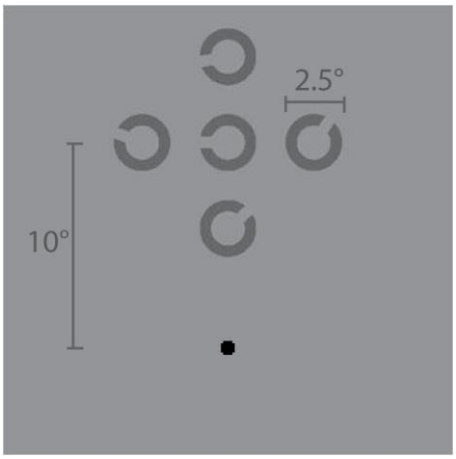

Figure 2.6 Sample trial on the letter contrast task. Observers determined the orientation of the central C. The contrast of the array of C's varied on an adaptive 3-up, 1-down staircase.

2.5.3 Word recognition

For the word recognition task, five letters were presented in the Arial font, 10^{o} above the fixation point at the centre of the monitor. The midpoint of these letters was centred at 10° above fixation (see figure 2.7). The letters were each 2.5° high, with an inter-letter spacing of 0.75 of a standard letter width (1.875°). The spacing was set quite close to the critical spacing for crowding, as increasing the spacing beyond this has little positive effect (and can worsen performance due to the increased eccentricity of the outer letters) (Chung, 2002).

The middle three letters spelled a word, drawn randomly from a bank of 200 common three-letter words (selected from a list of the most common words in the English language (Kilgarriff, 1997)). Two randomly selected flanking letters were presented on either side of the word. This procedure was

adapted from a previous study of peripheral reading rates (Latham & Whitaker, 1996). Successive letter strings were presented serially, and each string comprised a single trial. Participants were required to read each three letter word aloud, and the experimenter recorded responses. This task was made more difficult due to the crowding influence of the two outer letters. 'Crowding' refers to inappropriate combination of neighbouring stimulus features, and strongly interferes with visual tasks in the peripheral visual field (Levi & Carney, 2009). Stimulus duration was reduced in log steps of 0.15, and the starting stimulus duration was 1.76 seconds.

On trials where the calculated stimulus duration was not a multiple of the frame duration, it was rounded to the nearest integer number of frames. This technique was applied consistently across all observers (who each used the same stimulus durations).

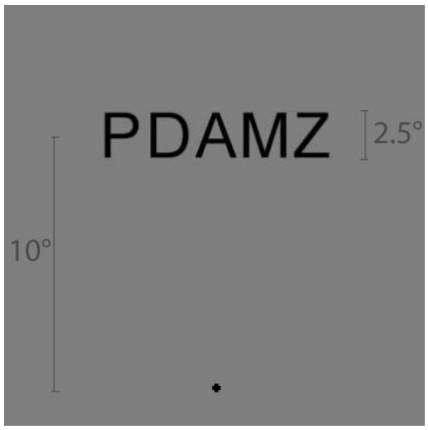

Figure 2.7 Sample trial on the RSVP reading task. Observers were asked to read aloud the word spelled by the central three letters. The stimulus duration varied on an adaptive 5-up, 1-down staircase.

Participants were requested to read the word spelled by the middle three letters aloud. There was no limit to their response time (though stimulus duration was limited as previously described). Responses in this study were coded by the experimenter, who also read the word aloud (after the observer's response) to confirm or correct the response. For a small number of words with commonly confused letters (e.g. OAT and CAT) errors were

classified as correct responses in the same way for each observer. All other words required three correct letters to be classified as a correct response.

After every five words, the experimenter altered the stimulus duration. If all five words were correct the stimulus duration was reduced, and it was increased if any one of the five words were incorrect. This was thus a modified 5-up, 1-down staircase.

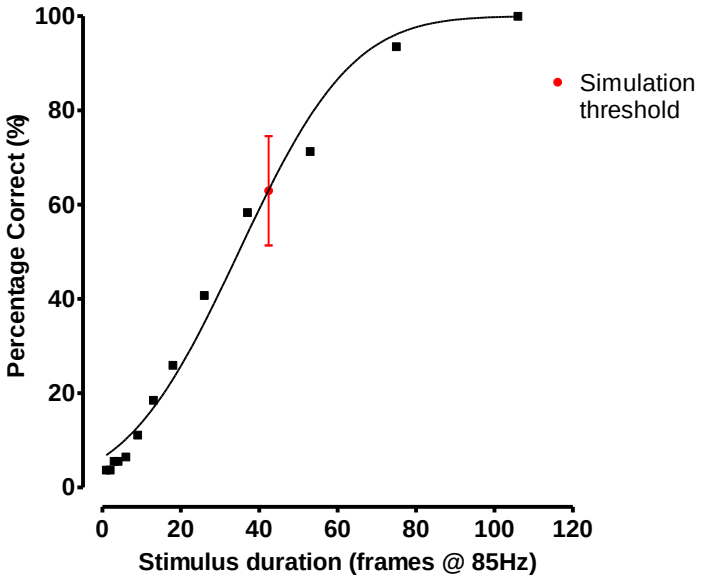

Figure 2.8 Psychometric function for the RSVP word recognition task, indicating the proportion of correct sets of 5 responses at each level of stimulus duration. The point on the function targeted by the modified 5-up, 1-down staircase is also shown.

As this type of staircase has not often been used, the location on the psychometric function that it targeted was unknown. In order to calculate this, a sample psychometric function was compiled based on the responses of the 29 observers from the RSVP reading task (figure 2.8). This function plots the relationship between the stimulus duration and the response of the observers, and can be fitted with a cumulative Gaussian curve ($r^2 > 0.99$). To calculate the point on this function targeted by the adapted 5-up, 1-down staircase, a simulation of the staircase was run in PsychoPy, using response probabilities taken from the psychometric function. This simulation was run 10,000 times and a mean value was mapped onto the function, as shown in

figure 2.9. Based on this data, the 5-up, 1-down staircase appears to target the 63% correct point on the psychometric function.

2.5.4 Letter acuity

This task was designed using the same principles as the Bailey-Lovie acuity chart (Bailey & Lovie, 1976), initially for use in a study on amblyopia (Astle, 2010). It was adapted in the current study to provide a reliable measure of peripheral visual acuity (figure 2.9).

A line of five Landolt Cs was presented within a crowding rectangular frame, on a white background (180cd/m^2). All sizes were set in proportion to the letter size (LS) for a given step. The crowding frame was 8*LS long and 2*LS high, while the Cs were positioned at -3*LS, -1.5*LS, 0, 1.5*LS and 3*LS. Therefore the edge-to-edge spacing between the letters and between the frame and the letters was 0.5*LS.

While fixating on the dot at the centre of the screen, participants were instructed to input the orientation of the gap in each C in turn (using the arrow keys on the keyboard). The current C was indicated by the smaller rectangular stroke beneath the array. Participants were observed for the first five training runs to ensure that they understood the task.

The initial size of the Cs was 1.5 logMAR (logarithm of the minimum angle of resolution). After the first set of five, the size of the entire array (Landolt C's, frame and indicator) decreased (step-size = log 0.2), and the participants worked through the next line. There was no time limit for the task, and it terminated when participants recorded 4 or more errors on one line (as in the Bailey-Lovie chart). The output of each run on this task was a single LogMAR measure.

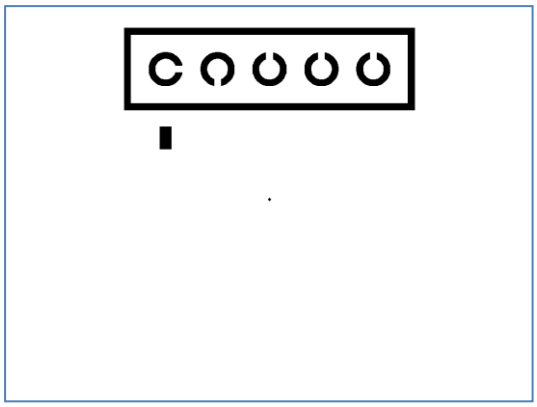

Figure 2.9 Sample trial on the visual acuity task. Observers determined the orientation of each C in the array, in sequence from left to right. Each subsequent array was reduced in size (by log 0.2), and the task terminated when the observer recorded four errors in any one line.

2.5.5 Crowding tasks

Three separate but related tasks were created to investigate the magnitude of crowding in the peripheral visual field. The core task was a basic crowded acuity task. Participants were instructed to read aloud the central letter in a cross-shaped array of five letters (see figure 2.10 for an example). The letter was then entered on the keyboard by the experimenter. Unlike in the word recognition task, no letter substitutes were permitted in this task.

The letter size was initially presented at 4° in height, well above the threshold of the observers, and the central letter in the array was centred at 10° above the fixation point.

The size of the entire array was varied on a 3-up, 1-down adaptive staircase, with variable step sizes of log .08, .05, .02 and .01. Step sizes were thus quite large initially, reducing in relative magnitude after each change of direction before settling at log 0.01. Unlike in the RSVP task the stimulus duration was constant at 0.15s (13 frames), and there were 100 trials on each run through the task. Observers inputted their responses directly using the keyboard. Correct responses were indicated by a high-pitched tone, and incorrect responses by a low-pitched tone. Thresholds were taken from the last 6 reversals on the resultant staircase.

Figure 2.10 Sample trial on the crowded acuity task. Observers were required to determine the identity of the central letter (N shown here). The size and spacing of the letters, or just the spacing, were varied depending on the condition.

In order to obtain a broader range of crowding measures, the task was repeated three times, with proportional letter spacings of 1.7, 2.0 and 2.6 letter multiples of letter size (centre to centre distance divided by letter height). An uncrowded version of this task was also implemented, in which a single letter was presented at 10° above the fixation point. There were no flanking letters in this condition, and this task was in all other respects identical to the crowded task.

A third task was also implemented to further investigate crowding in peripheral vision. Again this task was very similar to the initial, crowded acuity task. All of the initial parameters were unchanged, except for the spacing. This task begins with a proportional letter spacing of 2.6 times the letter size, and alters the spacing on an adaptive staircase, leaving the size at the initial value (3° in this task).

2.5.6 Fixation instability

Five related tasks were used to investigate the effect of instability of the target on letter acuity. The stimulus features and response protocols were largely identical to those used in the uncrowded letter acuity task, and participants were instructed to respond in the same way as on that task. The

experimenter coded their responses on the keyboard and monitored the first five sessions.

The targets in this experiment were designed to move within a defined region on the screen, which was centred at 10° above the fixation point. In all cases, the letter size was 3° and there were 100 trials in each run. Letter size was altered on a 3-up, 1-down adaptive staircase, using a set of log changes [0.08, 0.05, 0.02 and 0.01]. That is, the first step size was log 0.08, followed by log 0.05, and finishing with a number of steps of log 0.01.

The area within which the centre of the target could move was described by a circle of radius 0.855°, the same area described by Crossland's group as the average size of a preferred retinal locus (Crossland, Culham, & Rubin, 2004). Drift speeds of the target were taken from Whittaker (Whittaker, Budd, & Cummings, 1988).

The magnitudes of discontinuous movements (simulating saccades) were drawn from a normal distribution based on data from a study of saccades and eye-drift (Møller, Laursen, & Sjølie, 2006). This distribution had a mean of 0.8° and standard deviation of 0.26°. This places these movements within the range of "large microsaccades" described in Moller et al. (2006), and allowed for movements across a large proportion of the space occupied by the PRL. For simplicity, these movements occurred within one frame. That is, the target was redrawn in its new location on the frame following its disappearance from the original location. This is unlike normal saccadic motion, which involves acceleration and deceleration at the start and end (respectively) of the movement.

The starting position of the target was randomly drawn from a normal distribution. The mean of this distribution was set at 10° directly above the fixation point, and its standard deviation was set such that the edge of the locus of movement was a distance of 2 standard deviations from the centre. The five different tasks are described below.

Static target

In this task, a single letter was presented with a random starting position, and remained in that position on each trial. This task was thus very similar to the uncrowded acuity task. However, there were five separate conditions of this task, each of which used a different stimulus duration. The durations used were 0.15, 0.49, 0.82, 1.16 and 1.49s. Each observer completed two runs at each of the five stimulus durations, to a total of ten runs in all.

Dynamic target

Similar to the previous task, a single letter was presented with a random starting position. In this task the target was set to move with a range of drift speeds (0.328, 0.661, 0.995, 1.327 and 1.663 degrees per second), with a random starting direction. If the centre of the target reached the boundary, a new random heading was assigned. Each of these conditions was further subdivided into the five stimulus duration levels detailed in the previous task. With two runs at each level, each observer thus completed fifty runs on this task. See table 2.1 for a breakdown of the various sub-conditions of the task.

Drift Speed (°/s)	Stimulus duration (s)
0.328	[0.15, 0.49, 0.82, 1.16, 1.49]
0.661	[0.15, 0.49, 0.82, 1.16, 1.49]
0.995	[0.15, 0.49, 0.82, 1.16, 1.49]
1.327	[0.15, 0.49, 0.82, 1.16, 1.49]
1.663	[0.15, 0.49, 0.82, 1.16, 1.49]

Table 2.1 A breakdown of the 25 different conditions used in the "dynamic target" task.

Static, simulated saccades

The basic stimulus in this task is identical to that in the *static target* task. However, in this task target position was manipulated to simulate a saccade (i.e. to move instantaneously to a different position within the defined area) in a random direction at various intervals. Between saccades the target remained motionless. Five different conditions were set up in which the intervals between saccades were manipulated. The time between saccades

were the same as the stimulus durations used in the previous tasks; i.e. 0.15, 0.49, 0.82, 1.16 and 1.49s. However, in this task the stimulus duration was always set at 1.49s, so in the longer duration conditions only a single saccade was performed. The crucial parameter here may thus be the latency to the first saccade.

Dynamic, simulated saccades

The basic stimulus in this task is also identical to that in the *dynamic target* task. However, the stimulus duration was always set at 1.49s, and the drift speed at 0.995 °/s (the median drift speed). As in the *static, simulated saccade* task, five conditions were set in which the target was also set to simulate a saccade at intervals of 0.15, 0.49, 0.82, 1.16 and 1.49s, while still moving between saccades.

Dynamic fixation

The final condition was unlike the others in an important respect. In this condition a single, static target letter was presented at 10° above the usual fixation point at the centre of the screen. However, the fixation point itself was set with a random drifting motion identical to that used for the target in the *dynamic target* condition. Observers were required to maintain fixation on this point (which was reset on every trial to the usual position of the fixation).

The first four conditions examine every combination of a drifting and 'saccading' target (table 2.2). The fifth condition replicates the *dynamic target* condition, but transposes the movement of the target onto the fixation point.

	Target drifts?	Target 'saccades'?
Static target	No	No
Dynamic target	Yes	No
Static, simulated saccades	No	Yes
Dynamic, simulated saccades	Yes	Yes

Table 2.2 The four primary conditions within this study examine every combination of a drifting and 'saccading' target, to examine the relative contribution of each to letter acuity.

2.5.7 AMD reading

The stimuli in this task were similar to those used in the RSVP reading task, and the method of responding was identical. In the AMD reading task, however, a different sort of fixation point was required. Recall that individuals with age-related macular disease have no central vision. Therefore, the use of a central fixation point would have been impossible. With this in mind, a large whole-image diagonal cross was generated at the centre of the screen (see figure 2.11).

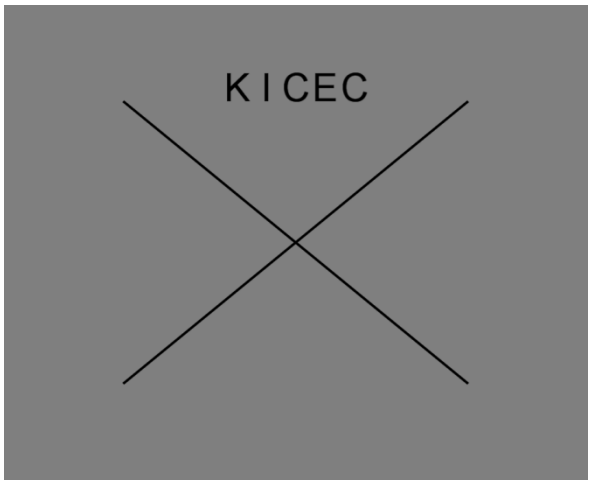

Figure 2.11 Sample trial on the AMD reading task. Observers were asked to read aloud the word spelled by the central three letters. The stimulus duration varied on an adaptive 5-up, 1-down staircase. The diagonal lines were used to allow individuals with central blindness to maintain approximate fixation at the centre of the screen.

Each diagonal was 28.4° long in total, and subtended an angle of 39.3° to the horizontal. The diagonals were 0.25° thick. The use of such large diagonals

allows individuals with large central scotomas to maintain some degree of central fixation. This task ran an adaptive 5-up, 1-down staircase, and terminated after 8 reversals.

2.5.8 Other diagnostic tests

A variety of diagnostic and other tests were used in the course of these experiments. Observers were screened for cognitive deficits using the Mini Mental State examination (Folstein et al., 1975). It was discovered early in the testing process that the most elderly participants quickly became fatigued during testing. Therefore it became essential to minimise the amount of time spent on each task, where this could be done without prejudicing the screening process or results. The Mini Mental State has the advantage of being very brief (taking approximately 5-10 minutes to administer), as it contains only 11 items. Although it concentrates only on the cognitive components of mental functioning (neglecting mood and abnormal thought processes) it was felt that this was sufficient for the purpose of this study. The items used on this test can be found in Appendix C.

Our RSVP reading task is intended to train and assess word recognition ability under very specific and constrained circumstances. In an effort to understand how this ability might generalise to more externally useful reading skills, we also assessed our macular disease observers with the MNRead Acuity chart (Mansfield, Ahn, Legge, & Luebker, 1993).

The chart displays sentences that descend in size by 0.1 logMAR, from 1.3 logMAR (20/400) to -0.5 logMAR (20/6). Each sentence contains 10 words (60 characters) distributed over 3 lines, in a serif font (Times Roman). The participant reads through the sentences until they reach a sentence in which no words can be identified. The number of errors and time taken are recorded. This can be used to derive three measures of a participant's reading ability. There are several methods for interpreting its outputs, but a lack of consensus as to which is preferable. We therefore chose to adhere to the manufacturer's instructions.

1. Reading acuity. The smallest size that the participant can read without making significant errors. Reading acuity is then recorded in logMAR as:
   Acuity = 1.4 – (sentences x 0.1) + (errors x 0.01) (2.4)
2. Maximum reading speed. The participant's reading speed when reading is not limited by print size. It is recorded in seconds as:
   Reading speed = 60 x (10 – errors) / (time) (2.5)
3. Critical print size. The smallest size that the participant can read with maximum speed. This is subjectively recorded as the inflection point on the curve of print size versus reading time.

2.6 Perceptual training protocols

The perceptual learning protocols used in each task are all similar to one another. The experiments had three distinct phases: a pre-training day, a training phase (of varying length) and a post-training day. On the pre-training day a number of measures were recorded, including some screening tasks. The training phase then focused on training a single task. Training occurred at the same time each day for 10 or 15 days (weekdays only), depending on the task. In this way it was possible to observe the effect of training on a particular task. In the post-training phase some of the measures from the pre-training phase were re-examined, which made it possible to observe any transfer of improvements from the trained to the untrained tasks.

2.7 Analysis

As previously stated, adaptive staircases were used in the majority of the tasks employed by this study. In these cases, the geometric mean of the final six reversals was recorded as a measure of the observer's threshold. In the perceptual learning studies observers had five runs on the trained task each day. The mean of the individual thresholds was calculated to provide a daily threshold. The majority of learning curves were fitted to the daily thresholds

using a one-phase exponential decay regression (Graphpad Prism). The equation for this curve is shown in equation 2.6 (where K is the rate constant, expressed in the reciprocal of X units).

$$Y = (Y_0 - Plateau) * exp(-K*X) + Plateau \quad (2.6)$$

Pre-post ratios (PPR) were calculated as a measure of within-subject improvement on trained and untrained tasks. These are calculated by dividing an individual's daily threshold on the last day of training by their daily threshold on the first day of training. Thus a PPR of 1.0 indicates no improvement; 0.5 indicates a 50% improvement; 0.2 an 80% improvement; etc.

Unless otherwise indicated, error bars represent the standard error of the mean. These were calculated for the (combined) daily thresholds in the learning studies. However, observers in the crowding and fixation tasks only had two or less runs on each condition. In these cases, the standard error was calculated from the data comprising the final six reversals in each staircase.

T-tests or ANOVAs (with Bonferroni post-hoc comparisons) were used to assess the statistical significance of threshold differences between tasks and conditions. Where this was not possible, probability testing and bootstrapping were carried out in MatLab R2011a, using programs adapted from a previous study (Moore, McCabe, Duckworth, & Sclove, 2002). Bootstrapping is a technique in which the original data set is resampled (with replacement) several thousand times (Efron, 1979; Efron & Tibshirani, 1993). As it uses sampling with replacement, the same data point can appear in a sample more than once (or indeed not at all).

In this study bootstrapping was used in place of more traditional tests, to determine whether or not there was a difference between specific data sets (i.e. to see if training had improved performance significantly, pre- and post-training thresholds would be compared). In this case, after each sample any differences between the relevant data sets were assessed. This was repeated

10,000 times for each comparison, in order to provide a robust assessment of the significance of any differences observed in the data.

Chapter 3: Perceptual learning in the peripheral visual field

3.1 Introduction

Individuals with late-stage macular disease are often restricted to viewing with their peripheral vision alone. As we have seen, peripheral vision is severely impaired relative to central vision, in a number of ways. A great deal of research has examined specific visual functions that are impaired in peripheral vision, such as visual acuity (Westheimer, 2001), resolution (Johnson & Leibowitz, 1979), reading speed (Lee, Kwon, Legge, & Gefroh, 2010; Yu, Cheung, Legge, & Chung, 2010), fixation stability (Tarita-Nistor, Gonzalez, Markowitz, & Steinbach, 2009) and identifying second order (i.e. contrast defined) letters (Chung, Levi, & Li, 2006). All of these tasks are amenable to some improvements using perceptual learning techniques – however, the wider application of these improvements is currently unknown. With rehabilitation of individuals with macular disease in mind, it is important to know what types of perceptual learning might induce the greatest magnitude of useful (to an observer with macular disease) improvements with the least amount of training.

Three tasks were selected to examine this issue, each of which reflects an important aspect of peripheral (and general) visual function. The tasks that were initially chosen were crowded word recognition, contrast sensitivity, and position discrimination. These tasks were chosen as they each tap into aspects of visual functioning that are known to be more difficult for people with macular disease – reading, low contrast viewing (contrast sensitivity is reduced in the periphery compared to the fovea) and determining the precise position of small targets (e.g. people with macular disease have difficulty pouring water into a cup from a kettle). Training with these tasks has the potential to cover a broad range of issues relevant to people with macular disease.

The visual features used in our tasks are designed to be as similar as possible, in order to facilitate transfer of learning between tasks. They have been equated in terms of their size and spatial configuration, and the position and contrast task shared common spatial axes of judgement (which has been shown to facilitate transfer of learning between tasks (Webb, Roach, & McGraw, 2007)). All stimuli are presented at 10° above fixation (in the upper visual field). This position was chosen because the scotomas (area of blindness) experienced by people with macular disease generally do not extend beyond 10° eccentricity (Fletcher & Schuchard, 1997; Schuchard, Naseer, & de Castro, 1999). Therefore, developing a region of higher acuity in this area should prove useful even to those people most severely affected by macular disease.

In what follows, the characteristics of the perceptual abilities recruited by these tasks will be described, as will their potential for improvement through perceptual learning.

Visual acuity and hyperacuity

Visual acuity refers to the acuteness or spatial resolution of the visual system. It is primarily limited by the spatial density of photoreceptors (in the parafovea) and ganglion cells (in the periphery), but by optical factors in the fovea (Thibos, 1998) where the mosaic of photoreceptors is at its most dense.

In the fovea the sampling (Nyquist) limit of cones is roughly 1 arc minute (or a grating spatial frequency of 60 cycles per degree), which is close to the limitations set by the eye's optics (Levin & Adler, 2011). Foveal optical impairments thus have a strong effect. In the periphery, the optics change very little, but the dramatic drop-off in the density of photoreceptors leads to the dominant effect of photoreceptor density on visual acuity. Even when peripheral refractive errors are not corrected, peripheral spatial resolution is still likely to be dominated by photoreceptor sampling (Wang, Thibos & Bradley, 1997).

This type of acuity is generally measured by examining the ability to identify optotypes of varying sizes on a chart or computer-based task, and in such tasks the disparity between foveal and peripheral visual acuities is quite clear. Visual acuity is also affected by age even in optically corrected older adults (Owsley, 2011). It is therefore important to screen for participants with severely impaired visual acuity, as deficits of this kind would adversely affect task performance. Our visual acuity task uses an array of five Landolt C's, as described in chapter two.

Some studies have shown that visual acuity is not amenable to improvement with perceptual learning (Westheimer, 2001), although others have shown that letter-recognition can be improved under several conditions (Chung, 2007; Chung, Legge, & Cheung, 2004; Chung et al., 2006). It is likely that these differences arise due to the methods used to assess improvement – psychophysical visual acuity thresholds do not seem to be amenable to improvement, but percentage-correct and other measures do.

Visual acuity is chiefly limited by the spacing of photoreceptors in the retina. In contrast, hyperacuity allows spatial judgements to be made on scales even finer than the photoreceptor spacing (Westheimer, 1975). To do this, cognitive techniques such as super-resolution may be employed (Westheimer, 2012) – e.g. sub-pixel image localisation, where the centroid of a known stimulus can be used to determine its precise location (and thus its edges).

The three-dot bisection task used in this experiment is an example of a hyperacuity task. There are several different types of hyperacuity, including (but not limited to) stereoacuity (judgement of differences in depth), Vernier acuity (misalignment / alignment) and bisection tasks. In contrast to the others tasks in this study, hyperacuity is generally not affected by age (Lakshminarayanan & Enoch, 1995; Wang, Morale, Cousins, & Birch, 2009; Westheimer, 2001), but it is amenable to improvement with perceptual learning (Crist, Kapadia, Westheimer, & Gilbert, 1997; M Fahle, Edelman, & Poggio, 1995; Webb et al., 2007).

Contrast

Contrast sensitivity is generally thought to be a good predictor of deficits in spatial vision (Ginsburg, Evans, Sekuler, & Harp, 1982; Owsley, Sekuler, & Siemsen, 1983). As noted earlier, the ability to detect low-contrast stimuli is important in everyday life, and is significantly impaired in peripheral vision (Crassini, Brown, & Bowman, 1988; Levi & Carney, 2011). Reading speed also shows a general dependence on the contrast of the lettering, particularly at low contrasts (Legge, Rubin, & Luebker, 1987), and peripheral identification of low-contrast letters is affected even in the early stages of macular disease (Hahn et al., 2009). The ability to identify contrast-defined letters can be improved with training in peripheral vision (Chung et al., 2006), and sensitivity to contrast defined stimuli in extra-foveal vision can be equated with foveal sensitivity by scaling both size and second-order characteristics (Vakrou, Whitaker, & McGraw, 2007). One of the goals of this study was to examine the possibility of improving the ability to read low-contrast single letters in peripheral vision. Combined with our reading task, this task could provide important information on the direction that future rehabilitation programs for individuals with macular disease might take.

Reading & word recognition

Previous studies have shown RSVP reading to be amenable to large learning effects (Chung, 2011). It is superior to related alternatives such as trigram letter recognition and lexical decision tasks (Yu, Legge, Park, Gage, & Chung, 2010), and, unlike RSVP sentence reading, peripheral performance on single word RSVP reading can be equated with foveal performance (Latham & Whitaker, 1996). Reading of sentences in the periphery is known to be limited by the size of the visual span (Gordon Legge, Mansfield, & Chung, 2001; Yu, Cheung, Legge, & Chung, 2007), but it has been suggested that it may more accurately be said to be limited by the information transfer rate (visual span in bits / exposure time) (Cheong, Legge, Lawrence, Cheung, & Ruff, 2008). This implies that we could either increase exposure time or decrease visual span size to achieve corresponding improvements in legibility. In our word

recognition task we keep word-length fixed and explore the effect of stimulus duration. More participants were trained on this task than on the other two tasks, as initial testing demonstrated a larger proportional learning effect, and a larger effect of age. We therefore believe that this task may constitute the most suitable tool with which to examine the effects of age on perceptual learning.

Longevity of improvements

Changes associated with perceptual learning can be quite long-lived, up to 3 years in some studies (Karni & Sagi, 1993). Individuals with macular disease require rehabilitative strategies that provide long-term benefits in order to minimise any potential cost-benefit trade off. Therefore it is important that the types of learning employed in these studies will lead to perceptual changes that can be retained over time.

In studies on amblyopic observers, improvements in position discrimination (Li & Levi, 2004) and contrast sensitivity (Zhou et al., 2006) were retained up to one year after the training program had ended. Similarly, perceptual learning of letter recognition and RSVP reading speed have led to improvements stable at three months post-training (Chung et al., 2004). Given these findings, it is expected that some retention of improvements will be observed following perceptual learning of the tasks in the current study.

Study aims

In this study observers will be engaged in a randomly assigned program of perceptual learning on one of the trained tasks (word recognition, position acuity, or contrast sensitivity). The overall magnitude of learning on each task will be determined, as will any transfer of learning to the other tasks (between-task learning). Observers assigned to each task will have a cross-section of ages, allowing the determination of any effects of age on their respective task.

3.2 Methods

3.2.1 Observers

Data was collected from 57 individuals with corrected-to-normal vision. The age of these observers ranged from 17 to 81 years, with a mean age of 48 and a standard deviation of 20 years. 35 of the observers were female, and 23 were male. All observers scored within the normal range on the mini-mental state exam, and no ocular pathologies were reported or detected during screening.

3.2.2 Stimuli

The word-recognition task used three letter words presented in the Sloan font. However, the staircase for the word-recognition task was initially designed with a ceiling at 1.76s, which appears to have artificially limited initial thresholds. This ceiling was set as initial piloting did not indicate any higher stimulus durations would be required, and will be discussed in more detail in section 3.4.

The three-dot bisection task used Gaussian blobs. The letter acuity and letter contrast tasks both used Landolt C's. These stimuli are described in more detail in the General Methods (chapter 2).

3.2.3 Procedure

Participants were seated with their chin fixed at 57cm from the monitor. One eye was randomly selected to be the viewing eye, and the other was occluded using a patch. Auditory feedback was given for incorrect responses (the nature of which varied by task). The experiment consisted of three phases – pre-training, training and post-training.

The pre-training phase involved measurements of thresholds for the word-recognition, bisection, letter contrast and letter acuity tasks. Task order was randomised, and each task was repeated five times in a single session. This session lasted for roughly 60 minutes.

In the training phase, participants were randomly assigned to one of three tasks: letter contrast, word recognition, or bisection. Their assigned task was repeated five times each day, with a threshold recorded on each repeat. The majority of the observers (43 in total) had 8 training sessions. Five further observers had 13 training sessions. A final ten observers had no training sessions, as a form of experimental control.

The post-training was identical to the pre-training phase. Observers were once again measured on the word recognition, contrast and position tasks. Task order was randomised. The pre-training and post-training sessions were always carried out on separate days to the training sessions, with no gaps of more than 3 days between any two sessions. A summary of the procedure is shown in figure 3.1.

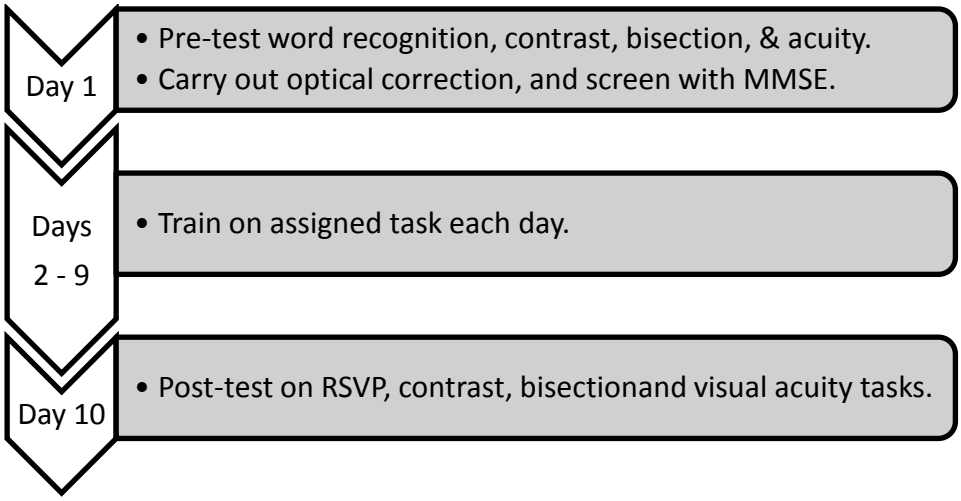

Figure 3.1: Experimental protocol. On days 1 and 10 all participants were tested on the word recognition, contrast, bisection and acuity tasks. Those in the experimental conditions trained on their respective task on days 2-9 (either word recognition, contrast, or bisection), while the control group had no training on these days.

The first and last sessions of the control group were identical to the experimental groups, and the intervening period was the same length for both experimental and control groups. The control group had no exposure to the tasks between these days. Providing no training in the intervening period was felt to be appropriate, as using control training in a different location or on a

different task could potentially have led to transfer of learning across retinal locations or between tasks (Jeter, Dosher, Liu, & Lu, 2010). An alternative method would have been to simply test our trained participants in a different retinal location as a control. Some research has suggested that attentional resolution varies in different parts of the visual field (He, Cavanagh, & Intriligator, 1996; Lee et al., 2010), potentially disrupting our ability to draw sound inferences from this type of testing. However, it is possible that alternative control conditions (e.g. watching a screen while performing an auditory task) may have provided a better control.

3.3 Results

3.3.1 Letter contrast task

Eight participants trained on the contrast task (median age=56.5, mean age=48.9, SD=21.5), though one participant was excluded due to an inability to maintain fixation.

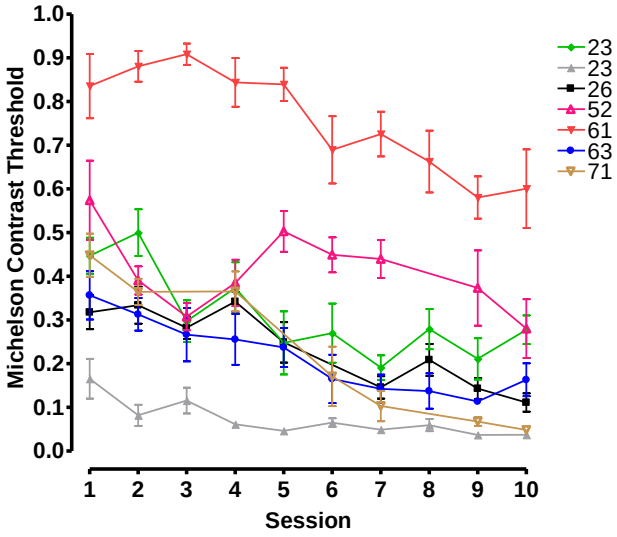

Figure 3.2: Within task performance for all participants on the contrast task, displayed in Michelson contrast units. All participants appear to show relative improvements on this task. Error bars represent the standard error of the mean.

Learning curves for this group across the 10 days of the study are presented in figure 3.2. Although all participants appear to have improved, it is difficult to determine from these learning curves alone if there is any pattern to the data. In order to understand any effects that may be obscured in the learning curves, we examined thresholds earlier in the training period (day 1) as well as on the final day of training (day 10).

Taken as a whole, there was a significant difference between day 1 (mean=0.45, SD=0.22) and day 10 (mean=0.22, SD=0.19) thresholds ($t(12)=2.13$, $p=0.027$, two-tailed). This general improvement can be seen in figure 3.2.

In order to investigate the effect of age on pre-training thresholds for this task, we pooled participants from the word-recognition, contrast, control and bisection groups (N=46, mean age=44.9, SD=20.3). This data is shown in figure 3.3, and indicates that pre-training thresholds are correlated with age ($r(44) = 0.61$, $p<0.0001$).

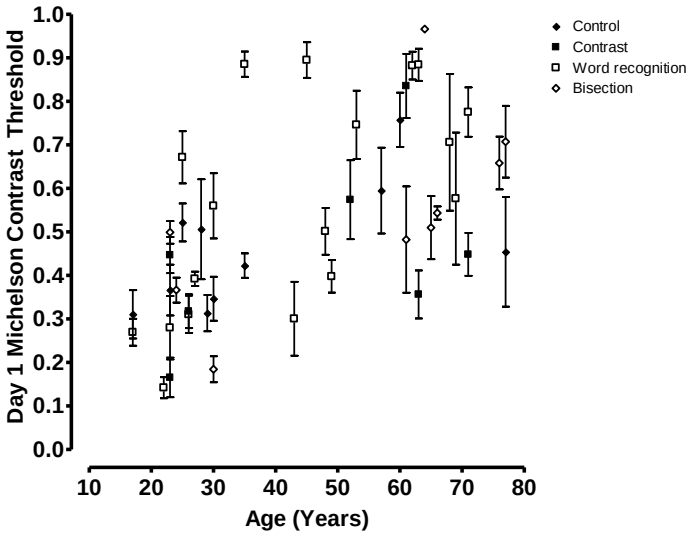

Figure 3.3: Combined day 1 thresholds for participants in the contrast, control, word recognition and bisection groups. Older participants recorded higher thresholds than younger participants. Error bars represent the standard error of the mean.

To explore a general effect of age, we also split this data into a 'younger' (N=23, mean age=26.4, SD=5.8) and 'older' (N=23, mean age=63.4, SD=9.8) group, using the median age (44) as the criterion. There was a significant difference between the contrast thresholds of the two age-groups ($t(44)=5.27$, $p<0.0001$, two-tailed) with the older group recording higher thresholds than the younger group.

The combined data indicates an initial age-related difference in thresholds on this task. However, by the end of our training period there appeared to be no age-related differences between the older and younger participants trained on the contrast task. A group comparison was not carried out due to the low numbers involved (N=7), but there was no significant correlation between age and final-day thresholds ($r(5) = 0.24$, $p=0.61$). However, this result may be attributable to the small sample size, as a similar analysis shows that there was also no correlation between age and day-one thresholds for the trained group alone ($r(5)=0.53$, $p=0.22$), in direct contrast to our analysis of the larger data-set.

In order to further assess the robustness of the improvements observed in the group as a whole, a 2-way repeated measures ANOVA was carried out on thresholds from the trained group (day 1 and day 10) and the control group (pre- and post-test). There was a significant main effect for session ($F(1,15) =7.47$, $p < 0.05$) and a significant interaction ($F(1,15) = 33.61$, $p < 0.0001$). A Bonferroni post-test indicated that the difference between conditions on day 10/post-test was statistically significant ($t = 2.65$, $p < 0.05$). That is, the mean threshold for the trained group on day 10 (mean=0.22, SD=0.19) was significantly lower than the mean of the control group (mean=0.38, SD=0.2) (figure 3.4).

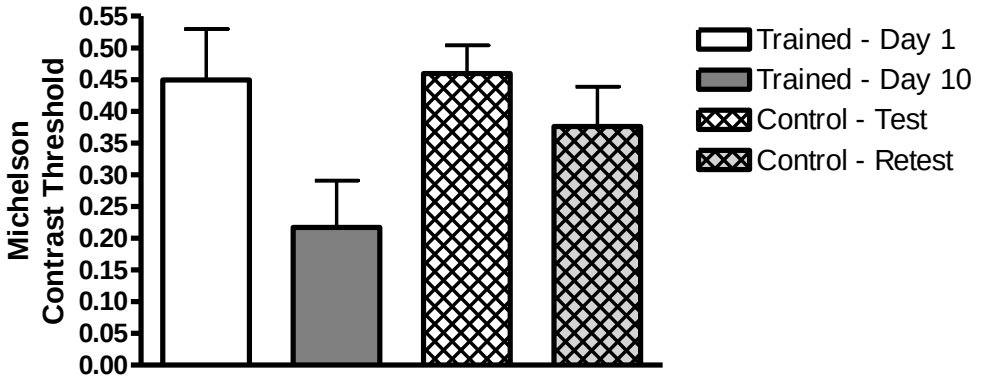

Figure 3.4: Thresholds for the trained group (day 1 and day 10) and the control group (test and retest). Error bars represent the standard error of the mean.

3.3.2 Bisection task

Ten participants completed training on the bisection task (median age=62.5, mean age=50.9, SD=22.9). Training data for this group (figure 3.5) indicates little change over the course of the ten sessions.

A 2-way repeated measures ANOVA was carried out on horizontal thresholds from the trained group (day 1 and day 10) and the control group (pre- and post-test). There was a significant main effect for session ($F(1,16) = 14.47$, $p = 0.0016$), indicating that significant improvement occurred over time. Day 1 thresholds for the trained group (mean = 0.34°, SD = 0.09°) were higher than those on day 10 (mean = 0.24°, SD = 0.09°), but a difference of a similar magnitude was observed between the control group's pre- (mean = 0.28°, SD = 0.09°) and post-thresholds (mean = 0.21, SD = 0.09). Bonferroni post-tests did not indicate a significant difference between control and trained groups on the pre-test ($t = 1.267$, $p > 0.05$) or post-test ($t = 0.46$, $p > 0.05$).

A second 2-way repeated measures ANOVA was carried out on vertical thresholds from the trained group and control groups. There was a significant main effect for session ($F(1,16) = 23.04$, $p = 0.0002$), indicating that significant improvement occurred over time. Day 1 thresholds for the trained group (mean = 0.45°, SD = 0.05°) were higher than those on day 10 (mean = 0.35°, SD = 0.08°), but a difference of a similar magnitude was observed between the control group's pre- (mean = 0.45°, SD = 0.07°) and post-thresholds (mean

= 0.36, SD = 0.07). Bonferroni post-tests did not indicate a significant difference between control and trained groups on the pre-test ($t = 0.15$, $p > 0.05$) or post-test ($t = 0.29$, $p > 0.05$).

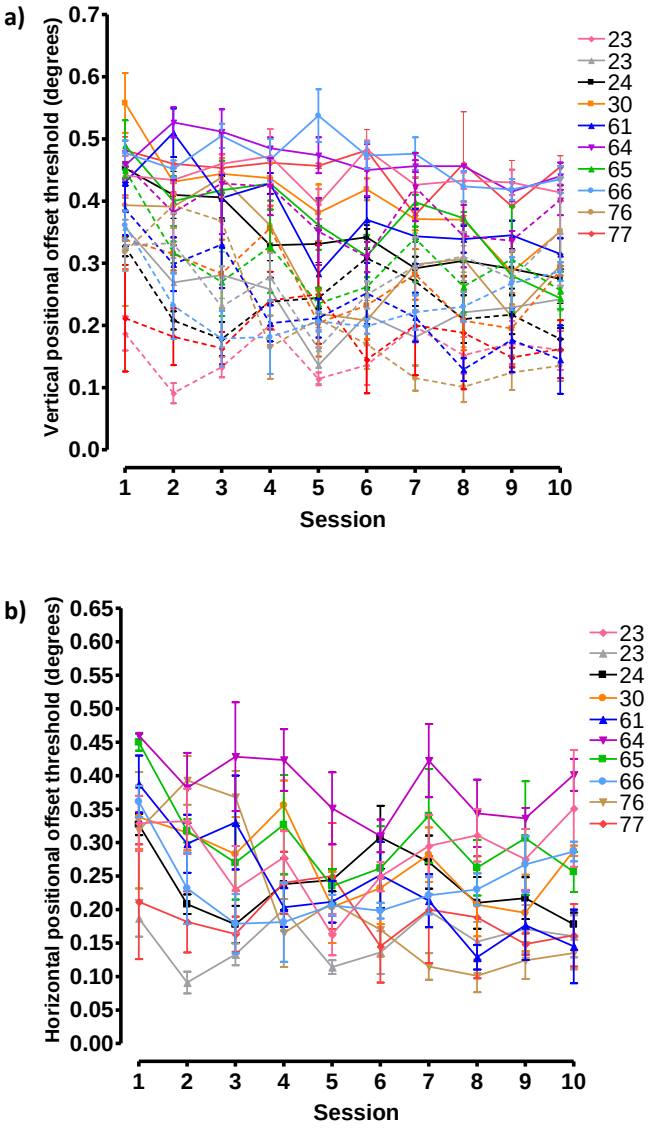

Figure 3.5: Learning curves for positional offset thresholds on the (a) vertical and (b) horizontal axes of the position task. Error bars represent the standard error of the mean.

As in the contrast task, we pooled participants from each group (bisection, word recognition, contrast and control) who had completed a pre-test on the bisection task. This enlarged group (N=35, mean age=44, SD=21.2) allowed us to investigate the effect of age on pre-training thresholds for this task. This data is shown in figure 3.6, and indicates that pre-training thresholds were not

correlated with age for either vertical thresholds (r(34) = -0.02, p > 0.05) or horizontal thresholds (r(34) = 0.2, p > 0.05).

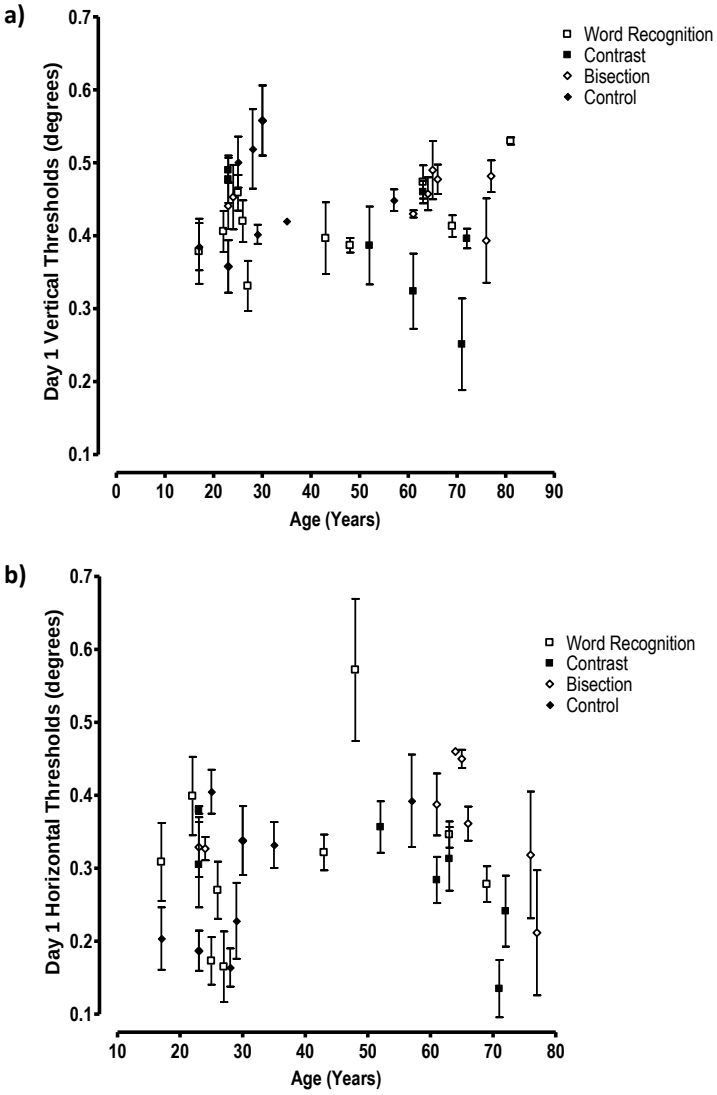

Figure 3.6: Combined day 1 thresholds on the (a) vertical and (b) horizontal axes for participants in the contrast, control, word recognition and bisection groups. Age was not correlated with thresholds. Error bars represent the standard error of the mean.

The only significant effect observed in this group is the difference in thresholds between the horizontal and vertical axes of the task. A 2-way repeated measures ANOVA indicated a significant main effect for axis ($F(1,18) = 13.19$, $p = 0.0019$) and also for time ($F(1,18) = 30.98$, $p < 0.0001$) as previously reported. Bonferroni post-tests indicated a significant difference between horizontal and vertical thresholds on both day 1 ($t = 3.21$, $p < 0.01$) and day 10 ($t = 3.03$, $p < 0.01$).

3.3.3 Word recognition task

Twenty-four participants completed 10 sessions (including pre- and post-training sessions) on the word-recognition task (median age=51, mean age=49, SD=19). Due to an observed difference in day-10 thresholds between our younger and older groups (see below), five of the older observers completed an extra five days of training in an attempt at closing the difference in thresholds (median age=61, mean age=63, SD=6). As in the other tasks, the word recognition group was subdivided into younger (n=12, mean=32.5, SD=11.1) and older groups (n=12, mean=65.2, SD=7.6).

The effect of training on the word recognition task is very clear. All participants showed improvements in their thresholds over the course of the training period. These improvements were modulated by the age of the participant. Figure 3.7, though extremely dense, provides a broad overview of the general pattern of improvements that were observed.

A 2-way repeated measures ANOVA was carried out on day 1/10 thresholds for the trained group and pre-/post-thresholds for the control group. Significant main effects for session ($F(1,31) = 48.24$, $p < 0.0001$) and group ($F(1,31) = 10.31$, $p = 0.0031$) were observed, and a significant interaction ($F(1,31) = 36.20$, $p < 0.0001$). Bonferroni post-tests indicated a significant difference between day 1 (mean = 1.42, SD = 0.13) and day 10 (mean = 0.69, SD = 0.37) thresholds for the trained group ($t = 10.88$, $p < 0.0001$), and between day 10 trained thresholds and post-test thresholds for the control group (mean = 1.29, SD = 0.18), ($t = 6.04$, $p <0.001$).

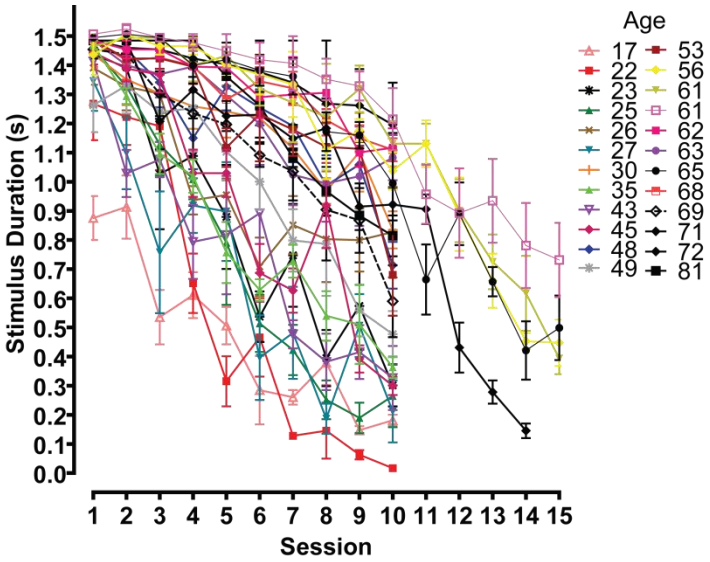

Figure 3.7: Learning curves across 10/15 days of training for the word recognition group. Thresholds for every participant improved over the course of training. Older participants improved to levels similar to younger participants following an extended period of training. Error bars represent the standard error of the mean.

As in the contrast task, thresholds recorded earlier in the training period can help to clarify the overall pattern of improvements. Figure 3.8 shows the thresholds on session 1 for all of the participants in the word recognition group, as well as all of the participants in the control group. Although some of the younger participants have recorded thresholds that are clearly lower than those of the older participants, this was counterbalanced by the large number of younger participants who recorded high thresholds.

This combined group (trained and control participants) was divided into younger (mean = 1.36, SD = 0.15) and older (mean = 1.43, SD = 0.09) subgroups by the median age (46). There was no significant effect of group on day 1 thresholds ($t(31) = 1.68$, $p = 0.103$, two-tailed).

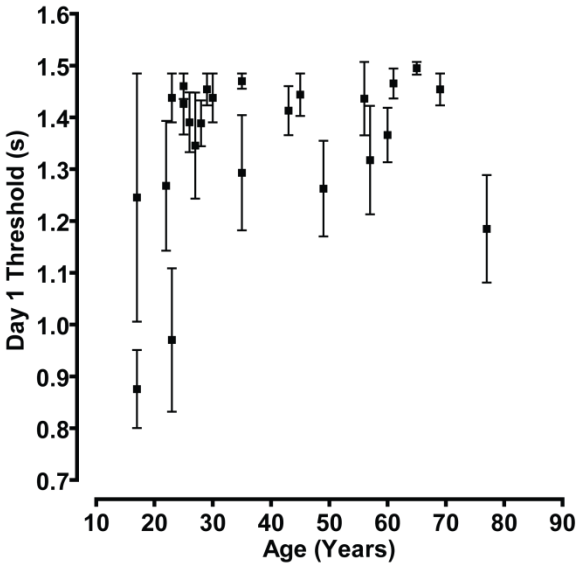

Figure 3.8: Day 1 thresholds for participants in the word recognition training and control groups. The y-axis is a measure of the stimulus duration, in seconds. There was no significant effect of age. Error bars represent the standard error of the mean.

As we have seen, by session 10 thresholds for younger participants in the training group were highly differentiated from those of older participants, both in raw values and in pre/post ratios (PPRs) (figure 3.11). Mean PPRs were significantly higher for the older group (mean = 0.67, SD = 0.13) than the younger group (mean = 0.29, SD = 0.18) ($t(22) = 5.89$, $p < 0.0001$, two-tailed).

Raw thresholds from the 10^{th} session are also correlated with age ($r(22)=0.72$, $p<0.0001$) (figure 3.9), with younger participants recording lower thresholds. This relationship is somewhat obscured by individual differences in the data, but it is further supported by the clear relationship between overall magnitude of learning and age (figure 3.10), where the magnitude of learning for younger participants (mean = 0.95, SD = 0.25) was observed to be greater than that of older participants (mean = 0.68, SD = 0.27) ($t(22) = 2.57$, $p = 0.017$, two-tailed).

Indeed, age is also correlated with the overall magnitude of learning ($r(22) = 0.54$, $p=0.0059$), again with younger participants showing a greater magnitude of learning. The magnitude of learning is not related to session 1 thresholds, which is unsurprising when we consider the lack of an age-effect on session 1.

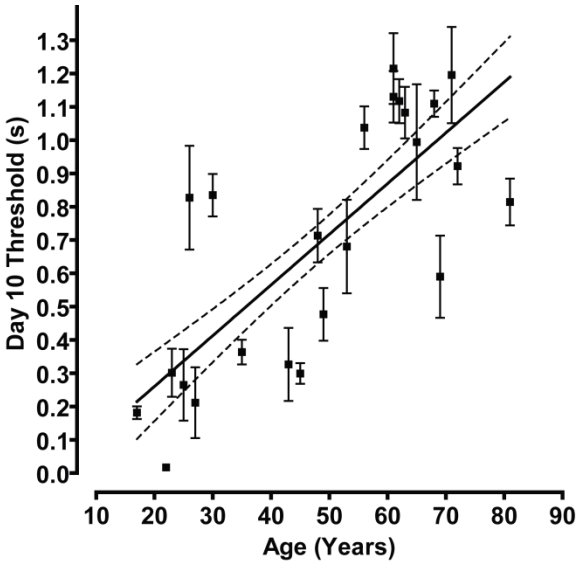

Figure 3.9: Stimulus durations at session 10 are linearly related to the age of the participant. Curves indicate the 95% confidence intervals for the linear regression. Error bars represent the standard error of the mean.

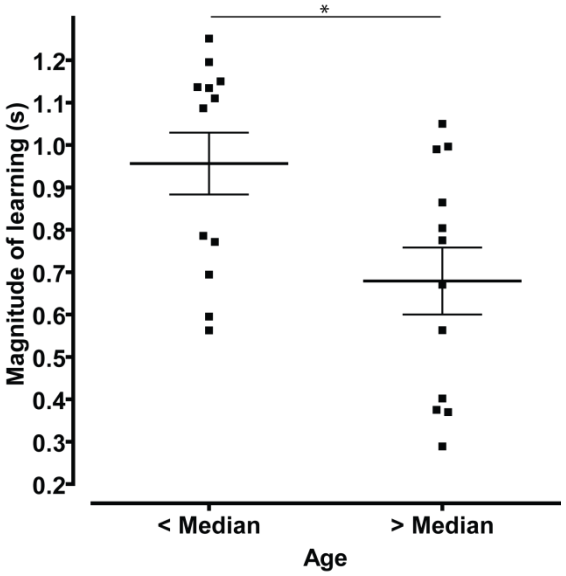

Figure 3.10: The magnitude of learning is greater for our younger group of participants. Error bars represent the standard error of the mean for each group.

The post-training thresholds recorded by our small group of older adults (n = 5, mean age = 63, SD = 6) who trained for 15 sessions were not significantly different to post-training thresholds for our younger group (n = 12, mean age

= 32.5, SD = 11.1) who trained for 10 sessions (t(15) = 0.32, p = 0.76, two-tailed).

The training curves for these two groups were also broadly similar (figure 3.11), and have been fitted with similar logistic curves (equations 3.1 and 3.2, both constrained between y-values of 1.5s and 0s). These curves explain a significant proportion of the variance in thresholds (R^2_{young}=0.97; R^2_{old}=0.99)

Age < median: $Y=1.5-(1.5/(1+exp((-(x-6.41)/3.02m2)))$ (3.1)

Age > median: $Y=1.5-(1.5/(1+exp((-(x-12.53)/3.27)))$ (3.2)

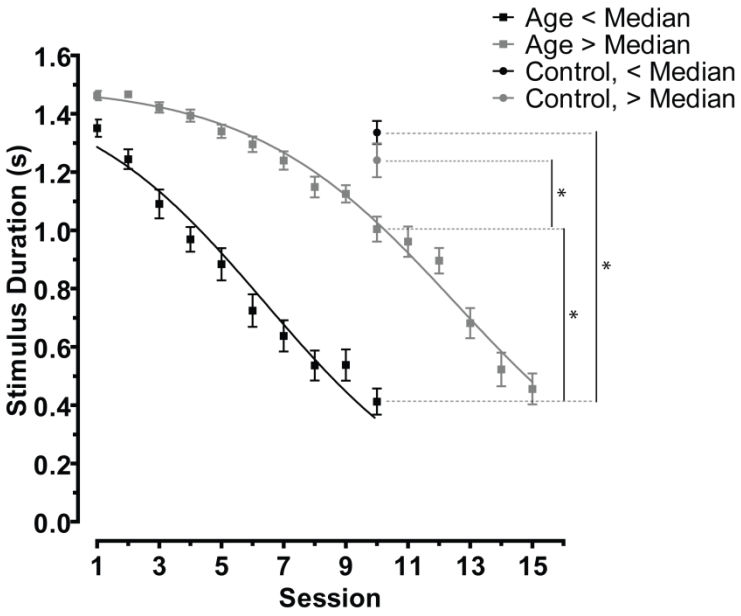

Figure 3.11: Grouped learning curves for the reading task. Data points after session 10 (for the older group) represent the mean of only 5 subjects. Thresholds for the younger group were lower by day 10 of training. However, an additional 5 sessions of training for a smaller subset of the older group eliminated the significant difference between younger and older post-training thresholds. Error bars represent the standard error of the mean.

A final condition was implemented in which no upper limit was set on the stimulus duration for the word recognition task. Given the large differences observed in the later stages of the study, it seemed surprising that no initial differences were observed between our younger and older participants. This effect is likely due to the imposition of an artificial ceiling on thresholds.

Therefore a version of the task was developed in which the stimulus duration was not limited (see the discussion section for further details).

A small group of older observers participated in this version of the study (N=5, median age=64, mean age=62, SD=8). Initially, thresholds for this group were higher than age-matched older observers in the normal condition (figure 3.12). On day 1, thresholds for this new group (mean = 2.57, SD = 0.27) were significantly different ($t(15) = 11.21$, $p < 0.0001$) to those of the original older group (mean = 1.34, SD = 0.17) that had been constrained by the threshold ceiling. By the fifth session, thresholds in this group had reduced in magnitude sufficiently to match the thresholds recorded by the original group. No significant difference between groups was observed at this point ($t(15) = 0.58$, $p = 0.57$).

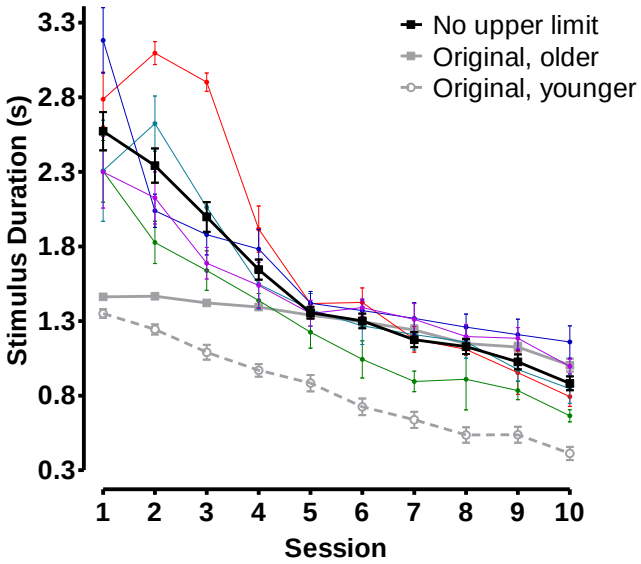

Figure 3.12: Individual and grouped learning curves in the word recognition task. The grey lines represented mean values for the original participants. The coloured lines indicate the individual learning curves of older participants in a condition with no upper limit on stimulus duration. Their mean learning curve (solid black line) can be seen to coincide with the learning curves of older participants in the normal condition. Error bars represent the standard error of the mean.

3.3.4 Pre/Post tests

In the word recognition and contrast tasks, participants demonstrated clear improvements in recorded thresholds. The development of functional improvements in the visual system (that could extend beyond the trained task) is an important goal of these experiments. Therefore, between-task learning was also examined in each of the trained conditions. As well as training on their assigned task, each participant recorded thresholds on the other tasks before and after the training period.

Although improvements were observed in the majority of between-task thresholds, these were rarely significantly different to the improvements observed in the respective control group. In order to eliminate the effect of differences in pre-training thresholds, we carried out ANOVAs on PPRs for each of the three tasks.

Word recognition

For word-recognition PPRs, there was a significant main effect of group $F(3,47)=15.73$, $p < 0.0001$. Post hoc analysis using the Bonferroni post hoc criterion for significance indicated that PPRs were significantly lower for the group trained on word recognition (mean = 0.49, SD = 0.24) than for the control group (mean = 1.01, SD = 0.11) ($t = 6.46$, $p < 0.001$) and the group trained on the bisection task (mean = 0.8, SD = 0.21) ($t =3.89$, $p<0.01$).

The same analysis also shows that word recognition PPRs for the contrast-trained group (mean = 0.71, SD = 0.24) were lower than those of the control group (mean = 1.01, SD = 0.11) ($t = 2.91$, $p < 0.05$). This implies that training on the contrast task has some utility (in terms of word recognition ability) over and above that provided by the control condition.

Bisection

For bisection PPRs, a one-way ANOVA revealed no effect of group for either the vertical ($F(3,30)=0.19$, $p=0.89$) or horizontal conditions ($F(3,30)=1.27$, $p=0.3$). These results are likely due to the lack of any observable changes on this task.

Contrast

A Kruskal-Wallis one-way ANOVA was used to assess differences between the contrast task PPRs for each of our four groups. This test was necessary as Bartlett's test for equality of variances indicated that there were significant differences between the variances of our groups (Bartlett's statistic = 21.99, $p < 0.0001$).

The test indicates a significant effect of group (Kruskal-Wallis statistic = 8.80, $p = 0.03$). Pairwise comparisons were carried out with Dunn's multiple comparison test, which indicated that none of the differences in rank sum were significant (the largest difference was for the 'Control vs Contrast' comparison).

Visual Acuity

As well as between-task learning, we also recorded a measure of peripheral visual acuity in our final 14 participants (figure 3.13), all of whom were trained on the word recognition task. Although day 10 logMAR thresholds (mean = 1.19, SD = 0.15) were improved relative to day 1 thresholds (mean = 1.39, SD = 0.08), a repeated measures t-test indicated that the difference between sessions was not significant ($t(13) = 0.22$, $p > 0.05$, two-tailed).

Age was correlated with acuity on both day 1 ($r(12) = 0.66$, $p = 0.02$) and day 10 ($r(12) = 0.55$, $p = 0.04$), which is as expected (Gittings & Fozard, 1986). A cut-off point of 1.6 logMAR is often used in studies with older participants (Virgili et al., 2004), but all of the participants in the current study were within this limit.

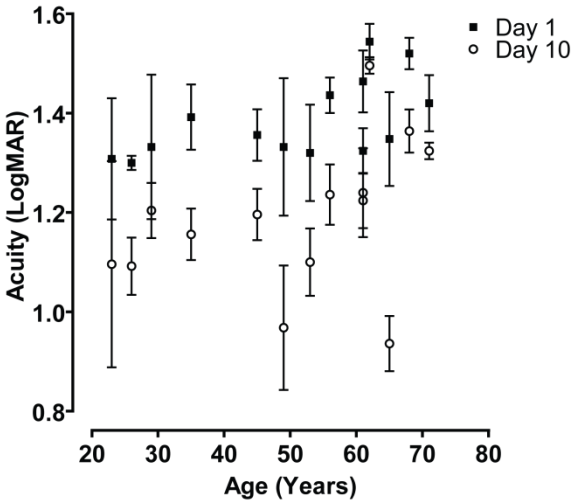

Figure 3.13: LogMAR (visual acuity) scores before and after training on the word recognition task. All participants showed slight improvements, but these were no greater than improvements in the control group. Error bars represent the standard error of the mean.

Retention of learning

Finally, a small subsample of observers was recalled at 6 months post-training to record a further set of thresholds on each of the tasks. Data for the word recognition task is shown in figure 3.14. Three groups were defined for this analysis: a young group (n = 5, mean age = 31), an older group that had trained for 10 sessions (n = 5, mean age = 53), and an older group that had trained for 15 sessions (n = 3, mean age = 63). These groups' thresholds were compared with each other and with thresholds from the control group's post-test using a one-way ANOVA. Pairwise comparisons were made with Bonferroni's multiple comparison test.

There was a significant main effect of group at 6 months ($F(3,71) = 28.15$, $p < 0.0001$). Control thresholds (mean = 1.294, SD = 0.17) were significantly higher than 6-month thresholds for the younger group (mean = 0.54, SD = 0.3; $t = 7.77$, $p < 0.001$) and the older group who had trained for 15 sessions (mean = 0.69, SD = 0.27; $t = 6.11$, $p < 0.001$). The younger group and the older group who trained for 15 sessions were not significantly different at 6 months ($t = 1.97$, $p > 0.05$).

These findings are in contrast to the older group who trained for 10 sessions. At 6 months, thresholds for this group (mean = 1.03, SD = 0.18) were significantly higher than that of the younger group ($t = 6.674$, $p < 0.001$) and the older group who trained for 15 sessions ($t = 4.46$, $p < 0.001$). Thresholds for this group were not significantly different to those of the control group ($t = 1.98$, $p > 0.05$).

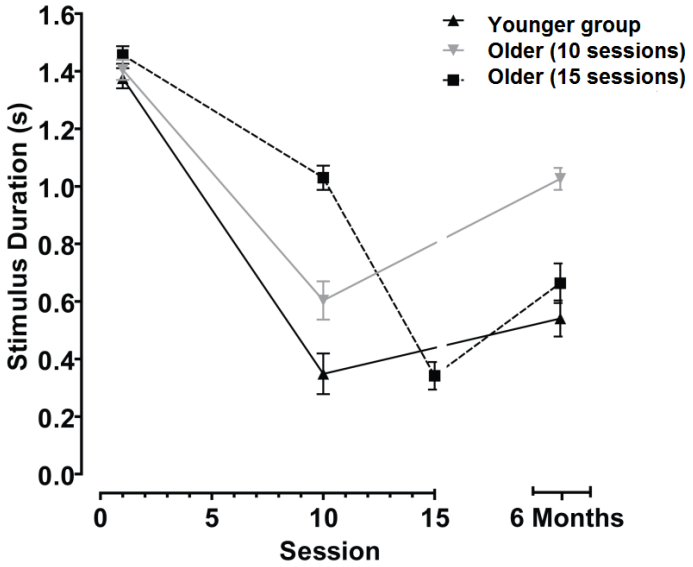

Figure 3.14: Preservation of word recognition thresholds at 6 months post-test. At 6 months, thresholds of the younger and older groups were significantly different, but the extended-learning older group was not significantly different to the younger group. Error bars represent the standard error of the mean.

3.4 Discussion

The aim of this study was to examine the potential extent of perceptual learning in the peripheral visual field, and to determine how this could be affected by age. A novel visual training program was developed for normally-sighted participants, requiring them to make judgements on stimuli presented in their peripheral visual fields. Should the recorded improvements prove to be behaviourally significant, then it may also be possible to induce functional improvements in the peripheral visual field of patients with macular disease.

Participants showed specific improvements on two of the trained tasks, providing further support for the presence of significant perceptual plasticity in the peripheral visual field. Training on the word recognition task led to large improvements in threshold (mean PPR=0.4, SD=0.26), as did training on the letter contrast task (mean PPR=0.46, SD=0.26). Training on the bisection acuity task led to smaller improvements in threshold (mean PPR=0.73, SD=0.26). However, improvements on the bisection task were not significantly different to the control group, indicating the absence of a robust learning effect. It is to this result that we will first turn our attention.

Bisection Task

The bisection task differs from the other two tasks in several ways. Crucially, this task requires the incorporation of visual information from the outer edges of our stimulus array, while the other two tasks require the exclusion of this information. In the bisection task, the outer two Gaussian blobs are used to determine the relative position of the inner blob. These outer blobs are positioned in the same part of visual space as the crowding C's in the contrast task, and the outer, crowding letters in the word recognition task. (Of course, it is only on the horizontal axis that the blobs coincide with the outer letters in the word recognition task.) Thus the bisection task requires the integration of information from a much larger region of visual space.

This process is made more difficult by the nature of these Gaussian blobs. Pilot testing indicated that stimuli with clearly defined edges made this task extremely easy – participants quickly reached asymptotic thresholds (that is, the central blob was at the centre-point) within the first session. We chose to use large Gaussian blobs to make the task more difficult (and hence to allow for learning). A further factor which may have increased the difficulty of the task is the size of the Gaussian blobs relative to the size of the increments on the staircase procedure (slightly less than one order of magnitude). The increased difficulty of the task resulted in none of our participants reaching asymptotic thresholds, even by the end of their training.

An alternative possibility is that participants' thresholds were not high enough to allow for improvements – we know that thresholds on simple tasks can more easily be improved when the initial thresholds are quite high (Manfred Fahle & Morgan, 1996; Sagi, 2011). Similarly, complex tasks can show greater improvements than simple tasks due to training (Ahissar, Nahum, Nelken, & Hochstein, 2009; Fine & Jacobs, 2002), which may be reflected in the superiority of learning on the reading and contrast tasks relative to the simpler bisection task. It is thus possible that individuals who trained on the bisection task were already at or close to their lowest possible threshold, which may explain the apparent lack of learning in this dataset. In future, increasing the eccentricity of the outer blobs may have allowed us to observe learning on this task – however, for the purposes of this study it was felt important to maintain a consistent spatial configuration in all of our tasks.

Data from the separated horizontal and vertical training reveals an orientation-dependent difference in ability (figure 3.6). Although initial thresholds on the two axes were different, their relative improvements due to training were very similar. Similar studies have also shown differences between horizontally and vertically aligned bisection tasks in peripheral vision – for example, Yap and Levi demonstrated a preferential ability on the equivalent of our horizontal condition (Yap, Levi, & Klein, 1987). This difference may be due to the configuration of visual receptive fields in the periphery, which tend to be larger and radially aligned. Thus radial (vertical) stimuli may fall onto a single large receptive field, while horizontal stimuli have a greater chance of falling across several receptive fields, increasing their discriminability. Crowding fields also tend to be aligned radially, meaning that the vertical condition may have been more crowded (Levi, 2008).

Unlike our other tasks, no effects of age were found on the bisection task. The lack of an age-effect in learning is unsurprising, given the general lack of learning on this task. However, we also observed no effect of age on initial thresholds. Some studies have shown that positional acuity tasks are resistant to the effects of age (Lakshminarayanan & Enoch, 1995; Latham & Barrett,

1998), though a more recent study with a similar three-dot bisection task showed a clear effect of age on optimum thresholds (Garcia-Suarez, Barrett & Pacey, 2004). Any age-related resistance could be stronger with 'fuzzy', low frequency stimuli such as our Gaussian blobs (Crassini et al., 1988), because the edges' lack of definition could increase thresholds in younger participants, while being unaffected by the optical degradation commonly found in older participants. If this is the case it implies that our task was not sensitive enough to detect any age-related differences in our participants. An alternative explanation is that our study lacked the statistical power to detect age-related differences in thresholds.

Contrast task

Unlike the bisection task, age-related differences were observed in the contrast task. It is well-known that contrast sensitivity is affected by aging (Crassini et al., 1988; Jackson & Owsley, 2003; Owsley et al., 1983), and this is reflected in our data. Although some participants recorded thresholds better or worse than we might expect for their respective age-groups (figure 3.2), it was clear that on the whole there was a general effect of age on the first day of training (figure 3.3), with younger participants achieving slightly better thresholds. Despite this early difference between the groups, thresholds at the end of training (and the overall magnitude of learning) appeared to be unrelated to age (figure 3.4). The largest age-difference (approximately 0.2 Michelson contrast units) was observed on session 2, and by session 10 this had reduced to approximately 0.1 contrast units. This reduction in the age-effect is partly explained by the strong correlation observed between session 1 thresholds and the overall magnitude of learning. The size of the differences between age-groups are in line with the size of the difference in contrast sensitivity reported elsewhere (Owsley, 2011) between older and younger observers.

Although the age-effect observed on day 1 was not present on day 10, we cannot conclude that our older participants overcame any observed deficit in ability. The overall magnitude of the change, and the lack of statistical power

for our post-test relative to the pre-test means that it is difficult to confidently infer a significant interaction with age.

Contrast sensitivity is thought to be a good marker for general visual function (Ginsburg et al., 1982; Owsley & Sloane, 1987), so improvements in this type of ability may have wider applications beyond the scope of this study. In this respect it is promising that training on the contrast task led to some improvement on the word recognition task, over and above improvements observed in the control group. Further testing is needed to determine the extent and nature of any transfer of learning. In particular, it would be interesting to determine whether or not our protocol could reliably improve reading speed, which is known to be affected by low contrast (Mitzner & Rogers, 2006).

Word recognition task

The most promising results came from the group who trained on word recognition. Improvements in recorded thresholds were observed for every participant, ranging between 20% and 98% reductions in the starting (pre-training) threshold. The mean improvement of younger participants was 70%, and 32% for older observers. In comparison, studies that trained RSVP reading of sentences report improvements of 53-72% in younger participants (Levi, Song, & Pelli, 2007; Yu, Cheung, et al., 2010), and 53% in older participants (Chung, 2011). The crucial difference is that participants in the current study were trained on the stimulus duration of single words. Under normal circumstances, single word reading is easier in the peripheral visual field (Latham & Whitaker, 1996). However, the words in this study were crowded while the words in the studies reported above were not. Despite these differences, we note that our results are of a similar magnitude to related tasks.

No effect of age was found on initial thresholds for this task. This result is unusual, as the majority of studies report a decline in peripheral reading ability with age (Hahn et al., 2009; Yu, Cheung, et al., 2010), again using

sentences rather than single words. However, in our study the upper limit of the stimulus durations was capped at 1.76s (150 frames). It was felt that stimulus durations beyond this length of time would provide no additional benefit to our participants, while also encouraging unwanted eye-movements. This duration is also significantly greater than the durations used for individual words in studies of RSVP sentence reading (Yu, Cheung, et al., 2010; Yu, Legge, et al., 2010), and greater than the 150ms minimum required for encoding during scene perception (Hegdé, 2008; Rayner, Smith, Malcolm, & Henderson, 2009) or reading (Blythe, Liversedge, Joseph, White, & Rayner, 2009) in foveal vision. Despite the fact that some participants do appear to be limited by this upper cap, we do not believe that allowing longer stimulus durations would have provided any additional benefit to learning.

In order to clarify this issue, a group of older observers were trained on this task with no upper limit on the initial stimulus duration (figure 3.12). Only older observers were used, as an examination of the individual learning data from younger observers clearly indicates that they were not limited by the capped starting duration. In figure 3.12 it can be seen that removing this cap releases the thresholds of the older observers upwards. Day 1 thresholds in this group become significantly higher than those of the younger observers ($p=0.001$), in line with the other RSVP reading studies mentioned above. This initial deficit in ability was quickly overcome – by day 5, thresholds in the uncapped group matched those of the capped group, and day ten thresholds were also of the same order. This unfortunate design issue has thus affected the initial data in this study, but the overall learning effect remains intact.

As well as the effects of stimulus duration noted here, crowding is also known to adversely affect reading ability in peripheral vision (Gordon Legge et al., 2001; Yu et al., 2007). Evidence from the letter contrast task provides an oblique hint at the impact of crowding on the word-recognition task. In the word recognition task, participants reported that they were unable to see any of the target letters clearly. However, participants in the letter contrast task reported that the central C was quite clear at high contrast levels. The target C

in this task is presented for a shorter duration than the initial stimulus durations in the word recognition task, which should make it more difficult to resolve. However, the spacing between it and its flankers is greater than the spacing in the word recognition task. This suggests that crowding may be responsible for at least the initial difficulties in resolve the target letters in the word recognition task, though this is by no means conclusive.

The effect of crowding can be reduced through training (Chung, 2011). If crowding is hindering performance on the word recognition task, then it is possible that a release from crowding is responsible for the rapid early learning phase observed in both younger observers and in older observers in the uncapped stimulus duration condition. Potentially, stimulus duration could become the main factor limiting performance only after a sufficiently large uncrowded visual span has been developed.

Previous studies have shown a reduction in plasticity in older populations (Burke & Barnes, 2006), which could certainly affect the rate or even the overall magnitude of learning on any perceptual task. A lower learning-rate could explain the higher thresholds of our older participants over the first few days of training. However, we would also expect a reduction in synaptic plasticity to affect any type of learning, such as that on the contrast task (where we observed similar learning curves for both age groups) if this were the case. The difference between these two tasks may be explicable in terms of the individual processing requirements – reading words peripherally requires increased top-down involvement (observed in frontal eye fields, superior and inferior parietal lobules, and parts of prefrontal cortex), particularly in older people (Szlyk & Little, 2009). It is possible that the simpler contrast task required less top-down processing, and so was more amenable to learning.

Given the higher initial thresholds observed in older participants in the word recognition task, it is unsurprising that day 10 thresholds are related to age (figure 3.9). On day 10 there is a significant effect of age, which is almost

entirely eliminated with 5 extra days of training (figure 3.12a). This matching of older and younger thresholds through extra training has been observed before, albeit in a motion discrimination task (Ball & Sekuler, 1986). It suggests that (in terms of final ability) there are no age-related qualitative differences on this task. The caveat here is that the effects of 5 days of extra training on our younger observers is unknown. It is possible that they too would have continued to improve their recorded thresholds, although ceiling effects would quickly come into play if the rate of learning remained constant.

Pre- & post-tests

One interesting consequence of training on these tasks was the observed between-task learning (and the lack thereof in some tasks). Participants were randomly assigned to a training condition, but also recorded pre- and post-training thresholds on the other tasks. No transfer of learning to the bisection task was observed, as would be expected given the lack of a significant learning effect even with training on that task.

Post-training comparisons for contrast data revealed some interesting patterns. Comparison of the contrast-trained and control groups on raw data indicated a significant effect of group, but this was not repeated for a comparison of the PPRs of the same groups. Training on the word recognition task also appeared to provide a slight benefit for performance on the letter contrast task relative to the control group. The magnitude of learning for the word recognition group was 0.24 contrast units, compared to 0.08 contrast units for the control group (PPRs of 0.60 and 0.92, respectively). This comparison was also found to be non-significant by the Kruskal-Wallis ANOVA.

To address these issues we ran a Shapiro-Wilk normality test on the Contrast PPRs (for the control group and groups trained on word recognition, contrast and bisection). This indicated that the contrast PPRs for the bisection-trained group were not normally distributed ($W = 0.78$, $p = 0.008$). We therefore ran a separate one-way ANOVA on the other three groups (which were normally

distributed), which indicated a significant main effect of group ($F(2,33) = 6.59$, $p = 0.0039$). Pairwise comparisons with the Bonferroni test then demonstrated significant differences for 'Control vs Contrast' ($t = 3.36$, $p < 0.01$) and 'Control vs Word' ($t = 2.91$, $p < 0.05$). This suggests that the non-significant pairwise comparisons from the Kruskal-Wallis test were partly a result of the bisection data. That said, we are cautious about inferring too much from these results, as our analyses have delivered contradictory results.

If there is a slight transfer of learning from word-recognition training to contrast detection, it may indicate the recruitment of related neural mechanisms by these two tasks, especially as the contrast task uses similar stimuli to the reading task, in the same position in visual space. Transfer of learning may not have occurred in the opposite direction (from letter contrast training to word recognition) because the contrast training was less crowded. As we have previously suggested, release from crowding may be crucial in the word recognition task.

Retention

The perceptual learning demonstrated by this data may have important implications beyond the scope of this study. However, demonstrating plasticity of the peripheral visual system would be of little clinical use if it were merely a transient phenomenon. In order to assess the duration of the plastic changes observed, follow-up tests were carried out approximately six months after the final day of training. Observers from the word recognition training group participated in this follow-up, since these participants demonstrated the largest overall improvements in threshold.

Each group recorded increases in thresholds at the follow-up (figure 3.16). Young observers recorded a statistically significant increase in mean threshold of 20% ($t(22) = 2.86$, $p = 0.009$, two-way). Older observers trained for 10 days recorded a significant 50% increase in threshold ($t(22) = 6.11$, $p < 0.0001$); and older observers trained for 15 days recorded a significant 29% increase in threshold ($t(18) = 4.54$, $p = 0.0003$).

As we have seen, the difference in group means of younger and older participants (trained for 10 sessions) at 6 months was significant. However, the group mean of older participants who trained for 15 days was not significantly different to that of the younger group at 6 months. This indicates that extending the learning period may prove to be an effective technique in developing long-lasting perceptual improvements. Such retention of learning suggests that significant perceptual plasticity is retained in the aging visual system.

Conclusions

In this study significant perceptual learning of features in the peripheral visual field has been demonstrated, as has a simple method of equalising the performances of younger and older participants. We believe that these findings may be due to perceptual plasticity in the visual processing stream. The nature of observed transfer of learning between the word recognition and contrast tasks suggests that these improvements may be a result of changes in higher-level decision areas of the visual processing stream, reweighting the basic (and similar) representations of these tasks on a task-specific basis. Previous models have suggested that perceptual learning induces changes late in the processing stream (Petrov et al., 2005; Schafer et al., 2007; Kahnt et al., 2011), and these are further supported by other models such as Reverse Hierarchy Theory (Ahissar et al., 2008) and a more recent multi-stage model of perceptual learning (Shibata et al,, 2014).

However, there are other potential explanations – for example, it could be suggested that redeployment of spatial attention is being learned. A separate study that carried out research on a similar task indicates that this is not the case (Lee et al., 2010). In Lee's study, deployment of spatial attention was measured in various locations around the visual field, before and after training on a trigram letter-recognition task. No changes in deployment of attention were observed as a result of training, which suggests that redeployment of spatial attention was not being learned in our task either.

Were our learning to be the result of learning deployment of spatial attention, we would also have expected greater transfer of learning between tasks.

It is also conceivable that the effect of age in this study may have been due to a decline in visual acuity (e.g. resulting from lenticular changes or nuclear sclerosis). However, unlike early studies similar to this that failed to correct participants' acuities for the specific task distance (which would have a negative effect on thresholds), we optically corrected every participant. We also screened each participant with the Mini-Mental State exam, to rule out the potentially confounding influence of cognitive decline. Therefore, we believe that the learning observed is indeed due to perceptual plasticity, and that the effect of age is specifically related to a decline in an aspect of perceptual plasticity. Extended training allowed us to equate the performances of younger and older participants, implying that this age-related decline in plasticity can be ameliorated and that it may be quantitative in nature.

The mean ages of our older training groups are older than the typical age of onset of macular disease. It is extremely promising for us that we observed such a marked improvement in their ability on the word recognition and contrast tasks. The ability to read is very important to people suffering from central vision loss, and recovering some of this ability would lead to an improvement in their quality of life. Such recovery would of course be of little benefit were it not maintained, so our 6-month retest scores are quite promising.

Maintenance of learned improvements will be an essential component in any prospective training program for individuals with loss of central vision. A macular-disease population trained in this manner would use the trained region every day, and so we would not expect as much slippage in their thresholds at a 6-month post-test.

Future training programs for individuals with macular disease will need to carefully account for individual differences. Scotoma size and pre-existing

PRLs vary across the population (Crossland, Sims, Galbraith, & Rubin, 2004), and the time-course of learning in a macular disease population can be extremely variable (Chung, 2011). We will also need to give some thought to how to bridge the gap between lab-based improvements and real-world improvements. One recent study indicated that eye-movement training elicited greater improvements than word recognition training, when tested on reading a block of text (Seiple, Grant, & Szlyk, 2011). However, the training program in this study was dissimilar to our own, and actual improvements on the trained tasks were not reported. We are hopeful that some form of simple word recognition training can have useful effects in a macular disease population.

Chapter 4: Crowding and ageing

4.1 Introduction

In chapter three, it was reported that peripheral word recognition is affected by age after training. It was hypothesised that two factors may account for this effect – crowding and / or stimulus duration. Both of these factors are known to adversely affect perception, albeit in very different ways.

Our concern in these experiments is the development of a potential programme of rehabilitation for individuals with macular disease, whose foveal vision is highly impaired or totally absent. It is therefore important to understand the precise nature of the deficits affecting performance on tasks such as word recognition. Knowledge of these processes is also of intrinsic interest to the wider fields of ageing and vision research.

Crowding is almost certain to play some role in the word recognition task. The crucial question that this experiment will address is whether or not it is likely to be responsible for the age-related deficits observed in the previous experiments.

What is crowding?

As described in chapter one, crowding is generally defined as the negative influence of neighbouring visual features on perception of a target feature (Flom, Weymouth & Kahneman, 1963, Stuart & Burian, 1962). It is thus an inhibitory interaction between features in the visual field. Its effects are felt quite strongly in the peripheral visual field, in the amblyopic fovea (Bonneh, Sagi, & Polat, 2007), and at a very small scale in the normal fovea (Levi, 2008; Levi, Klein, & Hariharan, 2002) (though foveal crowding is likely to be mediated by a different physiological process). Similarities between amblyopic vision and crowding in peripheral vision have sometimes led to the latter being used as a model for the former, but the accuracy of this comparison has been cast into doubt by a more recent study (Levi, Song, & Pelli, 2007). For now, we will focus on peripheral crowding.

It is important to note that crowding does not impair detection of a target – rather, it impairs discrimination or identification of the crowded target. The confusion between target and flanker is dependent on the similarity between the two, and it can take many forms (e.g. confusion of letter order (Chung & Legge, 2009)). Crowding is also strongly dependent on the eccentricity of the target. Bouma's law states that the crowding field (i.e. the spatial extent of crowding) is equal in size to 0.5 x eccentricity of the target (Bouma, 1970), and it has been suggested that the observed spatial extent of crowding represents a neuroanatomical constraint for object recognition in visual cortex. To be recognised, objects must be separated by 1mm in the tangential direction and 6mm in the radial direction in primary visual cortex (Pelli, 2008). At 10° in the peripheral visual field (as used in these experiments) it is thus possible for features as far away as 5° from each other to have a negative effect on their mutual identification or discrimination.

An interesting consequence of this eccentricity scaling is that we can scale the size of a stimulus array to equate performance at different eccentricities (Chung, 2007). To achieve this equivalence both the size of the stimulus features and the spacing between them must be proportionately scaled. This implies a second important feature of crowding – it is highly dependent on the centre to centre spacing between target and flankers. For word recognition and reading, performance improves as we increase the spacing between the letters up to the standard or critical spacing, after which performance worsens (Chung, 2002). Increasing the spacing beyond this point has the effect of moving the extremities of the stimulus array further away from the fovea, into an area of retina where acuity is reduced and positional uncertainty is increased (Yu, Cheung, Legge, & Chung, 2007). This strongly contributes to worsening peripheral reading ability (Falkenberg, Rubin, & Bex, 2007), and leads to a crucial tension between the spacing necessary to discriminate individual letters, and an economy in terms of the overall span of the word.

A final important feature of crowding in peripheral vision is that it is heterogeneous throughout the visual field. As noted above its effects become stronger with increasing eccentricity, and more eccentric flankers have a stronger crowding effect than less eccentric flankers (Levi, 2008) . Crowding fields are also larger in radial than tangential directions (i.e. the area over which inhibition can occur is greater) (Toet & Levi, 1992). One recent study has also indicated that crowding may be stronger in the horizontal meridian than in the vertical meridian (Petrov & Meleshkevich, 2011). Crowding is thus highly heterogeneous throughout the visual field, and this must be accounted for in studies of the issue.

Theories of crowding

A great deal is known about the effects of crowding, as described above. However, its origins remain uncertain. One early theory suggested that peripheral vision is affected by poorer attentional resolution than foveal vision (He, Cavanagh, & Intriligator, 1996). That is, the attentional resources devoted to peripheral vision were thought to be insufficient for making perceptual decisions, and that this was among the primary causes of crowding.

A thematically similar proposal arises from what we have already described about the size and scope of crowding fields in peripheral vision. Retinal and cortical receptive field sizes are known to be larger in peripheral vision, while optical qualities (at least for the central 10°) remain reasonably constant. Larger receptive field sizes necessarily lead to a greater volume of information uptake per channel, presumably leading to difficulties with subsequent interpretation of this information. This is a bottom-up perspective – the basic information extracted from the scene is insufficient for making perceptual decisions. However, we have already seen that crowding does not generally affect detection of stimuli, which implies that it takes effect at a later stage in the visual processing stream.

Several lines of research have corroborated this and similar proposals, albeit without achieving any clear consensus on the precise nature of crowding. The feature integration (Levi, Hariharan, & Klein, 2002) or texture integration (Levi & Carney, 2009) stages have been proposed as likely candidates for crowding, with BOLD response differences observed in area V2 (Arman, Chung, & Tjan, 2006). We also know that crowding can occur when target and flankers are presented to different eyes (but in the same visual space), which implies a feature integration site of action. Levi has consistently proposed that crowding is simply a bottleneck on visual processing (Levi, 2008) – that the visual system experiences faulty integration downstream of the feature detection stage. As above, this may be due to the large integration fields associated with peripheral vision (which are of course an ecologically valid use of finite resources available to the organism). Area V4 is the first site in the visual processing stream with receptive field sizes equivalent to these integration fields, and activations in this area have been associated with crowding (Motter, 2002). This is one of many potential candidate areas and mechanisms for crowding, leading to the conclusion in a recent review that crowding occurs over multiple stages in the visual hierarchy (Whitney & Levi, 2011).

Crowding can also be quantified as a ratio between crowded acuity and isolated acuity. A recent study (Scialfa, Cordazzo, Bubric & Lyon, 2013) compared peripheral crowding using this metric between young and old groups of participants. The study measured participants' ability to detect the gap in a Landolt C, which was either at the top or bottom of the target, and was presented at 3° and 6° left and right of fixation along the horizontal midline. The degree of crowding was measured by assessing performance on the task with and without vertical bar flankers adjacent to the Landolt C target. The width of the flankers and the flanker-to-target separation was equal to the stroke width of the target (which was one fifth of the width of the letter). Crowding expressed in this way did not change with age. In other words, the target-to-flanker separation that enables target identification was

the same in younger and older individuals. However, the study found that absolute isolated and crowded acuity was worse in the older group.

Implications for this study

Crowding is an ubiquitous phenomenon in peripheral vision, and is thus likely to affect any study of this kind, particularly as reading in peripheral vision is inherently linked to crowding. The critical spacing for reading (below which performance drops off rapidly) is equal to the critical spacing for crowding (Levi, 2008). This implies that reading rate (or word recognition ability) are in some way proportional to the uncrowded visual span (Pelli et al., 2007) - the area in which crowding does not occur.

Perceptual learning studies have shown that the effect of crowding can be reduced through training – a potentially useful finding for the current experiment. One recent study concludes that the observed reductions in the spatial extent of crowding appear to reflect changes to the feature integration stage of visual processing (Hussain, Webb, Astle, & McGraw, 2012). However, these types of changes in the strength of crowding do not necessarily lead to improvements in reading speed (Chung, 2007). Similarly, word recognition rates can be scaled (size and spacing) across peripheral vision, but reading sentences with meaning cannot (Latham & Whitaker, 1996). This implies that peripheral vision is qualitatively inferior in interpreting sentences with meaning, which has clear implications for rehabilitation of individuals with macular disease.

However, the goal of the current experiment is not to improve reading speed or word recognition ability. Instead, we intend to assess the strength of crowding in a sample of normally sighted individuals of all ages. If differences in the strength of crowding are found to be associated with age (as in Scialfa et al., 2013), this may help to explain the age-related differences observed in our previous word recognition task. Unlike the word recognition task, here we surround our target letter with flankers on all four sides. Crowding is heterogeneous throughout the visual field, so utilising flankers in this way

reduces the likelihood of position affecting the results. (We would expect the results to be similar using this stimulus configuration on the horizontal meridian). Using a combination of flanked and unflanked acuity tasks, we intend to separate out the effects of resolution and crowding, and determine what relationship, if any, it has with age.

4.2 Methods

4.2.1 Observers

Data was collected from 56 individuals with corrected-to-normal vision. The age of these observers ranged from 18 to 76 years, with a mean age of 37 and a standard deviation of 20 years. 43 of the observers were female, and 13 were male. All observers scored within the normal range on the mini-mental state exam (mean value = 29.5), and no ocular pathologies were reported or detected during screening.

4.2.2 Stimuli

A target letter was presented 10 degrees above a fixation point. For measurement of uncrowded acuity, a single target letter was presented in isolation. For measurements of crowded acuity and spacing thresholds, an array of 5 letters were presented, configured in a cross shape, with the target letter in the centre and four outer letters along the cardinal axes (see figure 2.10). Letters were presented on a mean-luminance grey background (90 cdm^{-2}). Target and flankers were selected randomly from the following list of 10 letters which are approximately equally legible (Sloan, Rowland & Altman, 1952): C, D, H, K, N, O, R, S, V, Z. All letters were rendered in upper case Arial font.

4.2.3 Procedure

Participants were seated with their chin fixed at 57cm from the monitor. One eye was randomly selected to be the viewing eye, and the other was occluded

using a patch. Correct responses were indicated by a high-pitched tone and incorrect responses by a lower tone.

Critical spacing thresholds were measured by varying the flanker-to-target letter separation using a 3-up, 1-down adaptive staircase while letter size remained fixed. Initial flanker-to-target letter separation was set to 3 letter heights. The letter size used was equivalent to the acuity threshold from the crowded visual acuity task with the largest flanker-to-target separation (2.6 letter heights), which did not change with age. Crowded visual acuity with a 2.6 letter height flanker separation was always measured prior to spacing thresholds. The order of the other tasks was otherwise randomised for each observer.

A sample task order is as follows:

1) Crowded acuity (spacing set at 2.6 x letter size)
2) Uncrowded acuity
3) Crowded acuity (spacing set at 2.0 x letter size)
4) Spacing task
5) Crowded acuity (spacing set at 1.7 x letter size)

It should be noted that the spacing task differed from the other tasks in that it manipulated the spacing between the target and flanking letters (initially set at 3 x letter size) for a fixed letter size. All of the other tasks manipulated letter size at a fixed proportionate letter spacing.

For all tasks and conditions, stimulus duration was 153 ms (13 frames) and observers were required to identify the target letter and input their responses directly using a keyboard. All staircases terminated after 100 trials.

4.2.4 Data analysis

Each participant recorded a single threshold on each of the five tasks in this study. In order to assess the variability of their responses to the task, the standard error of the all of the data points contained in the last 6 reversals on each staircase was calculated.

ANOVAs were carried out to assess the significance of the differences in thresholds across the various tasks used in this study.

New measures used in this experiment include the crowding ratio and proportional spacing threshold. A crowding ratio was calculated for each participant at each level of the crowding task. The ratio is calculated as:

$$\textit{Crowding ratio} = \textit{crowded threshold} / \textit{uncrowded threshold} \quad (4.1)$$

This ratio is thus a measure of the strength of crowding at each of the three spacings used.

The letter size used in the 'spacing' task was based on the threshold from the crowded acuity task with spacing set at 2.6 times the letter size. A proportional spacing was thus calculated as:

$$\textit{Proportional spacing} = \textit{spacing threshold} / \textit{letter size} \quad (4.2)$$

This proportional spacing value allows direct comparisons to be made across participants, independent of the letter size used in each individual case.

4.3 Results

In this study, participants recorded thresholds on five different measures of letter acuity. There were four crowded versions of the task, and one uncrowded version. By comparing thresholds on these tasks the spacing-dependent strength of crowding can be assessed in each individual. Participants with a broad cross-section of ages were recruited to the study, which also allows an assessment of the effect of age on crowding. As well as assessing age on a continuum, we also split the data into younger (n = 31, mean age = 21.3, SD = 5.3) and older (n = 23, mean age = 59.3, SD = 9.7) groups, using the mean age (37.5) as the criterion.

The isolated letter acuity task provides a measure of observers' letter acuity without the deleterious effect of crowding. Figure 4.1 displays the threshold letter sizes achieved by participants on this task. No correlation was observed

between the age of the observer and the unflanked letter acuity threshold (r = 0.16, p = 0.26, two-tailed), nor was there any significant difference in the group means of older (mean = 1.08, SD = 0.21) and younger observers (mean = 0.98, SD = 0.24) (t(52) = 1.53, p = 0.13, two-tailed).

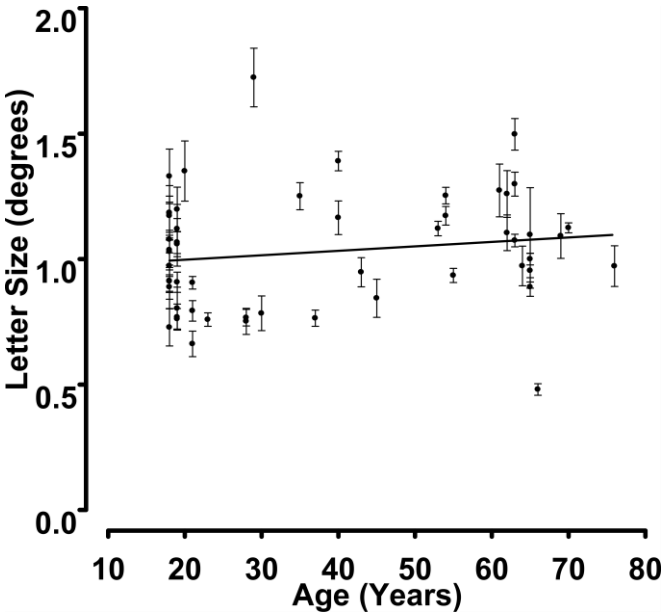

Figure 4.1: Letter size thresholds on the isolated letter acuity task. A linear regression has been fitted to the data to explore the effect of age on the sample. The slope of the regression line (0.0017) is not significantly non-zero (F(1,52) = 1.32, p = 0.26), and it does not effectively capture all of the variability in the data (r^2 = 0.02). Error bars represent the standard error of the mean.

Data from the isolated letter acuity task indicates that age does not have an impact on letter acuity thresholds in these conditions. The same set of observers also recorded thresholds on three crowded versions of the letter acuity task (figures 4.2 - 4). As with the uncrowded version, age does not appear to have affected letter size thresholds recorded on this task.

Figure 4.2 displays thresholds for the crowded letter acuity task with spacing set at 1.7 times the letter size. No correlation was observed between the age of the observer and the letter acuity threshold (r = 0.19, p = 0.15, two-tailed), nor was there any significant difference in the group means of older (mean = 4.42, SD = 1.22) and younger observers (mean = 4.07, SD = 0.73) (t(52) = 1.29, p = 0.20, two-tailed).

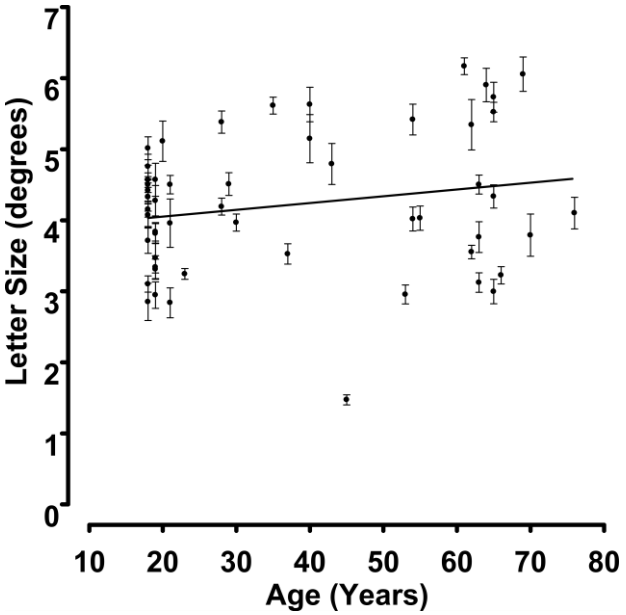

Figure 4.2: Letter size thresholds on the crowded acuity task, with letter spacing set at 1.7 x the letter size. Age is not related to thresholds. The slope of the regression line (0.0095) is not significantly non-zero ($F(1,52) = 2.16$, $p = 0.15$), and it does not effectively capture all of the variability in the data ($r^2 = 0.04$). Error bars represent the standard error of the mean.

Figure 4.3 displays thresholds for the crowded letter acuity task with spacing set at 2.0 times the letter size. No correlation was observed between the age of the observer and the letter acuity threshold ($r = 0.12$, $p = 0.41$, two-tailed), nor was there any significant difference in the group means of older (mean = 3.61, SD = 1.09) and younger observers (mean = 3.39, SD = 0.67) ($t(51) = 0.88$, $p = 0.38$, two-tailed).

Finally, figure 4.4 displays thresholds for the crowded letter acuity task with spacing set at 2.6 times the letter size. No correlation was observed between the age of the observer and the letter acuity threshold ($r = 0.09$, $p = 0.51$, two-tailed), nor was there any significant difference in the group means of older (mean = 2.76, SD = 0.92) and younger observers (mean = 2.60, SD = 0.48) ($t(50) = 0.83$, $p = 0.42$, two-tailed).

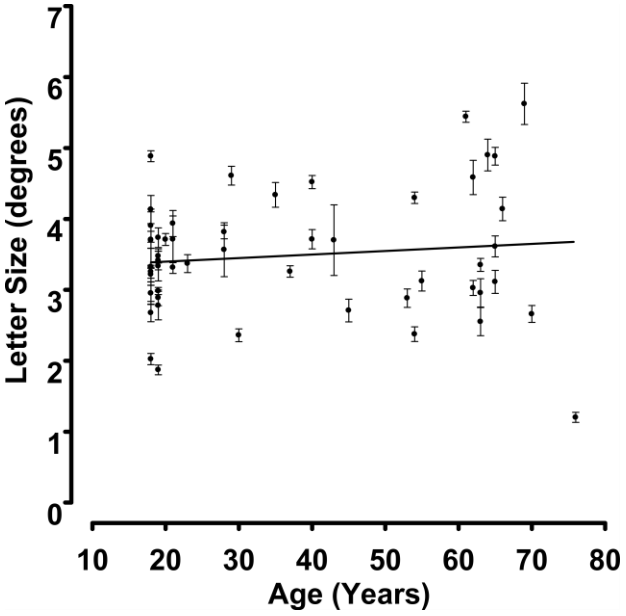

Figure 4.3: Letter size thresholds on the crowded acuity task, with letter spacing set at 2.0 x the letter size. Age is not related to thresholds. The slope of the regression line (0.005) is not significantly non-zero ($F(1,51) = 0.69$, $p = 0.41$), and it does not effectively capture all of the variability in the data ($r^2 = 0.01$). Error bars represent the standard error of the mean.

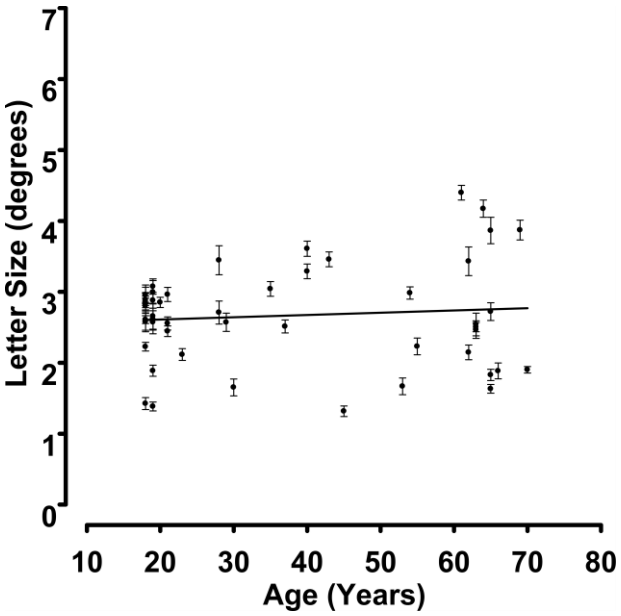

Figure 4.4: Letter size thresholds on the crowded acuity task, with letter spacing set at 2.6 x the letter size. Age is not related to thresholds. The slope of the regression line (0.0032) is not significantly non-zero ($F(1,50) = 0.43$, $p = 0.51$), and it does not effectively capture all of the variability in the data ($r^2 = 0.009$). Error bars represent the standard error of the mean.

Despite the lack of interaction between these thresholds and age, it is clear from this data that increasing the letter spacing allows for large decreases in threshold. The increased proportionate distance between target and flankers in figures 4.3 and 4.4 release the target from crowding, allowing observers to achieve lower letter size thresholds.

As age does not appear to be a factor in the thresholds recorded on these tasks, data from each task was analysed as a whole. A repeated measures one-way ANOVA indicates that there is a significant effect of task on the recorded thresholds ($F(3,50) = 5.60$, $p < 0.0001$). Pairwise comparisons (using the Bonferroni post-hoc test) indicated that the mean differences were significant for every comparison at $p<0.0001$ (see table 4.1 for the t-statistics for each comparison). That is, the thresholds recorded on the isolated acuity and each of the crowded acuity tasks are all significantly different to one another – with increasing crowding, thresholds become poorer.

	Isolated Acuity	**1.7xLS**	**2.0xLS**	**2.6xLS**
Isolated Acuity		32.65	25.57	16.79
1.7xLS	32.65		7.08	15.86
2.0xLS	25.57	7.08		8.77
2.6xLS	16.79	15.86	8.77	
Mean	1.02	4.25	3.55	2.68
SD	0.23	0.99	0.81	0.68

Table 4.1: Means and standard deviations for four acuity tasks, and t-statistics for pairwise comparisons between them (all significant).

These thresholds have been reported in unmodified letter sizes, without any form of correction. Although there was no main effect of age on visual acuity, it is still useful to examine the crowding ratios for these participants. Recall that the crowding ratio is essentially a measure of the strength of crowding that has been corrected for each individual's isolated letter acuity. Crowding ratios for each of the three crowded acuity tasks are shown in figures 4.5 – 4.7.

A one-way repeated measures ANOVA on the mean crowding ratios for each task indicated a significant main effect of task ($F(2,50) = 10.44$, $p < 0.0001$).

Bonferroni pairwise comparisons between the three tasks were all significant at $p < 0.001$ (see table 4.2). Increasing the spacing between target and flanker decreased the mean crowding ratio (indicating a reduction in the strength of crowding).

	1.7xLS	2.0xLS	2.6xLS
1.7xLS		6.41	15.31
2.0xLS	6.41		8.9
2.6xLS	15.31	8.9	
Mean	4.27	3.62	2.72
SD	1.12	1.15	0.81

Table 4.2: Means and standard deviations of crowding ratios for three crowded tasks, and t-statistics for pairwise comparisons between them (all significant).

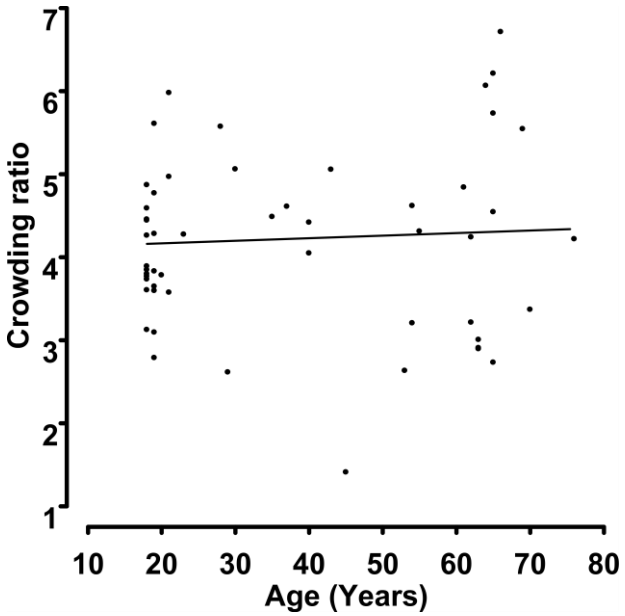

Figure 4.5: Crowding ratios for letter spacing set at 1.7 x the letter size. Age does not predict crowding ratios. The slope of the regression line (0.003) is not significantly non-zero ($F(1,52) = 0.16$, $p = 0.69$), and it does not effectively capture the variability in the data ($r^2 = 0.003$).

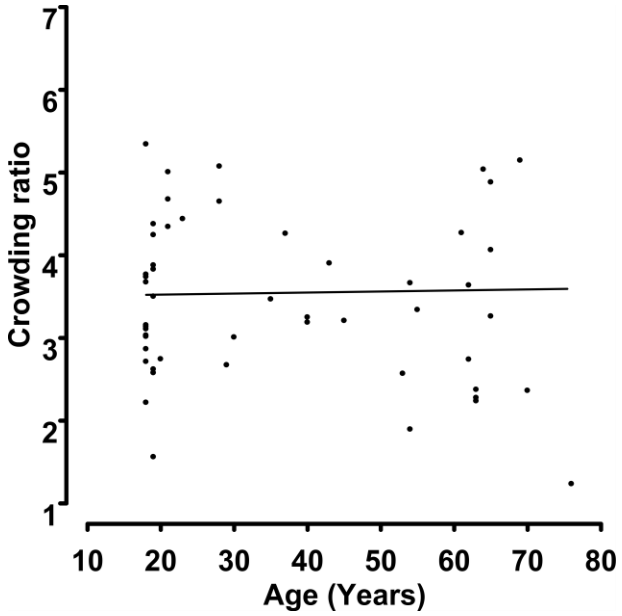

Figure 4.6: Crowding ratios for letter spacing set at 2.0 x the letter size. Age does not predict crowding ratios. The slope of the regression line (0.001) is not significantly non-zero ($F(1,51) = 0.02$, $p = 0.88$), and it does not effectively capture the variability in the data ($r^2 = 0.0004$).

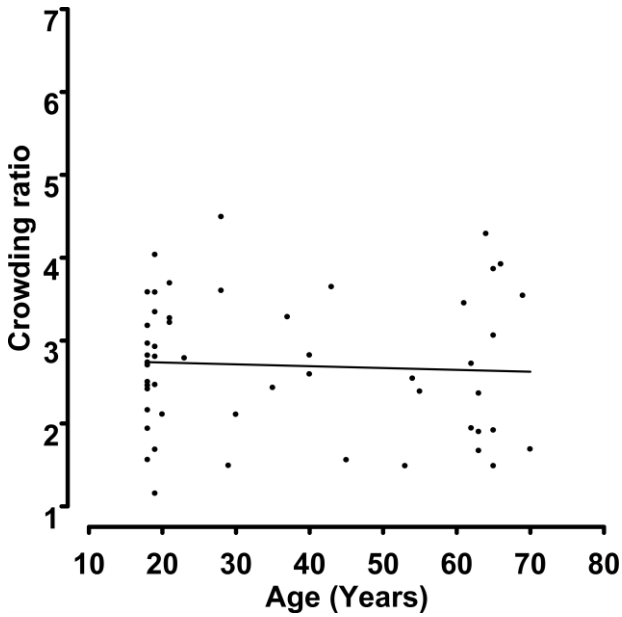

Figure 4.7: Crowding ratios for letter spacing set at 2.6 x the letter size. Age does not predict crowding ratios. The slope of the regression line (-0.002) is not significantly non-zero ($F(1,50) = 0.14$, $p = 0.71$), and it does not effectively capture the variability in the data ($r^2 = 0.003$).

Data from all three tasks is shown together in figure 4.8. The crowding ratio for every participant is above the identity line (at which level there would be no difference between flanked and isolated letter acuity). This indicates a stepped effect of crowding at every level of the task.

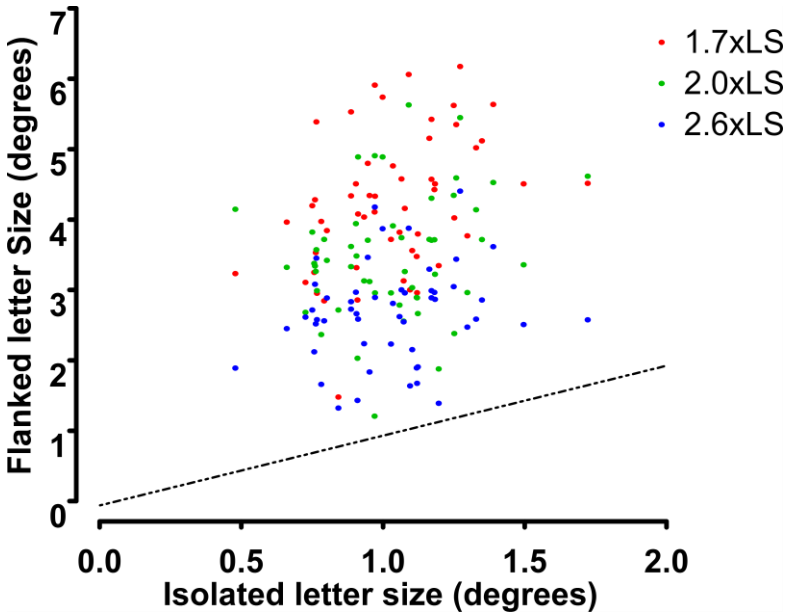

Figure 4.8: Crowding ratios for all three crowded acuity tasks. The ratios are all above the identity line (dotted line, where the ratio of flanked to unflanked ratios is equal to zero). Increasing spacing reduces the crowding ratio, indicating a release from crowding.

Finally, the letter spacing task provides further data on the relationship between crowding and age. The letter size in this task was set differently for each observer, using the threshold letter size recorded on the crowded acuity task with spacing equal to 2.6 x the letter size. The spacing was manipulated on this task, holding letter size constant.

Manipulating spacing instead of size did not lead to any age-related effects on this task (figure 4.9). No correlation was observed between the age of the observer and letter spacing thresholds ($r = 0.12$, $p = 0.39$, two-tailed), nor was there any significant difference in the group means of older (mean = 4.55, SD = 1.6) and younger observers (mean = 4.16, SD = 0.72) ($t(52) = 1.21$, $p = 0.23$, two-tailed).

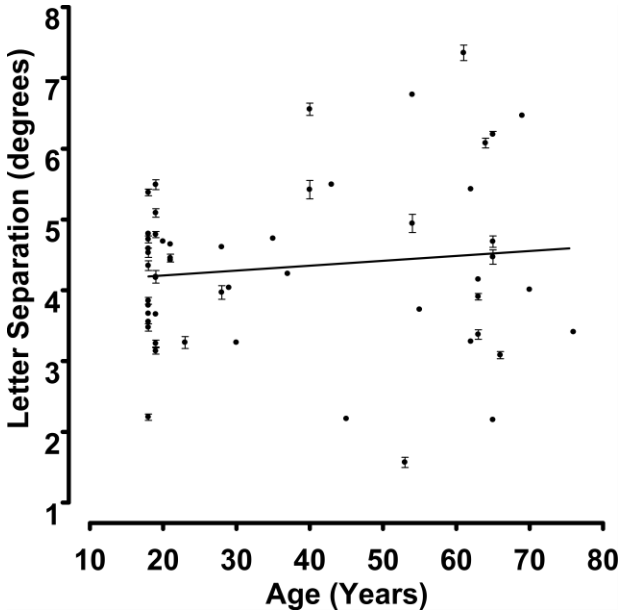

Figure 4.9: Spacing (letter separation) thresholds. Age does not predict letter spacing thresholds. The slope of the regression line (0.007) is not significantly non-zero ($F(1,52) = 0.75$, $p = 0.39$), and it does not effectively capture the variability in the data ($r^2 = 0.014$).

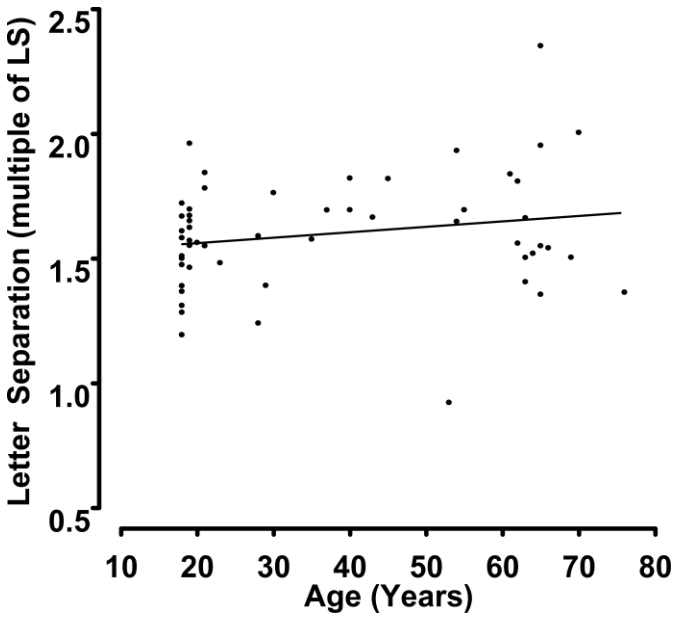

Figure 4.10: Normalised letter spacing thresholds. Age does not predict thresholds. The slope of the regression line (0.002) is not significantly non-zero ($F(1,52) = 1.98$, $p = 0.17$), and it does not effectively capture the variability in the data ($r^2 = 0.036$).

Analysis of the corrected letter spacing threshold (figure 4.10), with spacing thresholds normalised to letter size, also failed to reveal any effect of age. No correlation was observed between the age of the observer and corrected letter spacing thresholds ($r = 0.19$, $p = 0.16$, two-tailed), nor was there any significant difference in the group means of older (mean = 1.66, SD = 0.28) and younger observers (mean = 1.56, SD = 0.17) ($t(52) = 1.59$, $p = 0.12$, two-tailed). The mean letter spacing threshold is 1.6 times each observer's individual letter size (SD = 0.23).

4.4 Discussion

This data reveals an interesting example of the preservation of visual function in old age. It appears that perception of crowded letters does not worsen with age, which places this ability in an unusual position. Many diverse visual functions worsen with age, including contrast sensitivity (Owsley, Sekuler, & Siemsen, 1983), visual search (Madden, 2007), peripheral reading speed (Yu, Cheung, Chung, & Legge, 2006) and visual acuity (Gittings & Fozard, 1986).

There are a small set of visual tasks that are unaffected by age – some others include vernier acuity (Lakshminarayanan & Enoch, 1995) and spatial interval discrimination (Latham & Barrett, 1998). These two functions are both aspects of positional acuity, whose neural substrates are generally thought to be unaffected by age. It is interesting that perception of a crowded letter (a very different task) is seemingly also unaffected by the age of the observer.

The lack of an effect of age on crowding is a novel finding, but does not immediately clarify the effects of age observed in the previous experiment. Most notably, we observed a strong negative effect of age on perceptual learning of a word recognition task. We also observed a significant effect of age on letter acuity thresholds, which appears to be in direct contrast to the lack of such an effect in the current study.

Specific features of the current task(s) may help to explain these differences. The current task required the identification of a single letter directly above fixation. However, the word recognition task and the previous visual acuity task required participants to utilise information from a wider span at the same eccentricity (three letters and five letters, respectively). We know from previous research that it is the uncrowded visual span that is the primary bottleneck when determining reading speed, and also that the visual span shrinks with age (Falkenberg et al., 2007; Yu et al., 2006). It is thus possible that an age-related reduction in the uncrowded visual span may have contributed to the strong effect of age on the previous two tasks, while preserving the performance of older participants on the current (un)crowded acuity task.

It is also possible that our precise optical correction (which accounted for the task's working distance) may have helped to equalise performance across age. A similar study showed that corrected letter acuity is affected by age, but in that study perception of the target was impaired both by crowding and positional uncertainty (Falkenberg et al., 2007). This combination of factors may be sufficient to cause the differences between these two data sets. Our results indicate that the effect of crowding on single letter recognition may be constant throughout adulthood. The only variable which appeared to affect thresholds on these tasks was letter spacing, which has been previously noted to affect both word and letter recognition (Chung, 2002).

A previous study (Scialfa, et al., 2013) found no effect of age on visual crowding when it was quantified in terms of a ratio between crowded and isolated acuity. However, it found that both isolated and crowded acuity was worse in the older group. In contrast, we found no effect of age on crowded or isolated visual acuity. A number of differences between the two studies might explain these contrasting findings (this analysis first appeared in (Astle, Blighe, Webb & McGraw, 2014)).

First, the stimuli, task and task-requirements used in each study were different. The previous study used a two-alternate forced choice Landolt C task. It required subjects to detect the position of the gap, which was oriented either at the top or bottom (this could also be characterised as an orientation discrimination task). The present study used a letter identification task, where the target letter had to be identified from a set of 10 possible letters (ten-alternate forced choice task), chosen because it is more closely related to peripheral reading ability. It has been argued that crowding only occurs for recognition, and not for detection tasks (Levi, 2008, Levi, Hariharan & Klein, 2002, Livne & Sagi, 2007, Pelli, Palomares & Majaj, 2004), and that the reduced ability in detecting the gap in a Landolt C target flanked by bars may not measure crowding at all (Pelli et al., 2004).

Second, some older participants in Scialfa's study (2013) had visual health problems. For example, one participant had glaucoma, one had loss of peripheral vision, and five had cataracts. Although post hoc analysis revealed no difference in the crowding ratio between older participants with and without self-reported vision problems, it does not remove the possibility that those with visual problems had higher isolated and crowded peripheral visual acuity thresholds, which might have influenced the differences found between the young and older groups (Scialfa et al., 2013).

Third, the targets were presented at different eccentricities in the two studies. Scialfa et al (2013) presented stimuli at 6° or 9° from fixation along the horizontal midline, while we presented targets 10° above fixation (see chapter 2 for a discussion of this decision). Because the target was randomly presented at either 6° or 9° left or right of fixation in the Scialfa (2013) study, subjects did not know where the target was going to appear. Target recognition in the periphery is highly dependent on the deployment of attention (Talgar, Pelli & Carrasco, 2004). Randomly presenting the target at different locations introduces spatial uncertainty and is likely to change the attentional demands of the task. Visual attention gets worse with age (Madden, 1990) and older individuals, who perform more poorly at tasks

requiring visual attention (Ball, Owsley, Sloane, Roenker & Bruni, 1993, Plude & Hoyer, 1986, Steinman, Steinman, Trick & Lehmkuhle, 1994), are likely to perform worse when the location of a target is uncertain. This is connected to the useful field of view, the area of visual field that an individual can rapidly and accurately process visual information, which has been shown to reduce with age (Ball, Beard, Roenker, Miller & Griggs, 1988) and may explain the higher acuity thresholds found in the older group by Scialfa et al. (2013). The present study eliminates this influence by ensuring the eccentricity that the target is presented at remains fixed (at 10° above fixation).

Our study also sheds light on the relationship between crowding and surround suppression. Surround suppression refers to the mechanism whereby a high contrast surround reduces the perceived contrast of a centre stimulus, and is thus conceptually similar to crowding. Supporting this similarity, both crowding and surround suppression show radial-tangential anisotropy (Petrov & McKee, 2006, Toet & Levi, 1992), and tuning for orientation (Levi et al., 2002, Petrov, Carandini & McKee, 2005) and spatial frequency (Chung, Levi & Legge, 2001, Petrov et al., 2005). Additionally, their effects scale with eccentricity (Bouma, 1970, Petrov & McKee, 2006, Toet & Levi, 1992) and do not depend on stimulus size (Petrov & McKee, 2006, Strasburger, Harvey & Rentschler, 1991). However, unlike crowding, surround suppression does not show inward-outward anisotropy (Petrov, Popple & McKee, 2007) (but see also : van den Berg, Roerdink & Cornelissen, 2007), and occurs only when the contrast of the surround is greater than the target contrast (Chubb, Sperling & Solomon, 1989). There is evidence that surround suppression changes with age though this has been reported as either an increase (Karas & McKendrick, 2009) or decrease (Betts, Taylor, Sekuler & Bennett, 2005) in the effects. Our finding that crowding does not change as a function of age, adds further evidence to support the idea that crowding and surround suppression are mediated by distinct mechanisms.

In conclusion, there are several important points to note from this data. First, it seems clear that crowding does not have as large an impact on the older

visual system as might be expected. This has implications for any age-related visual rehabilitation program, in which crowding might now be considered to be less of a factor (depending on the tasks involved). Second, many of the papers referred to in the introduction conceptualise crowding as a consequence of erroneous feature integration in the visual processing stream. The current data suggests that preservation of generalised feature integration is preserved to a large extent into old age, though again this possibility requires further testing. Related to this, these results provide further evidence that crowding and surround suppression are mediated by different underlying mechanisms.

Chapter 5: Unstable fixation and letter acuity

5.1 Introduction

Eccentric viewing is hampered by a number of factors. In previous chapters we have looked at the difficulties presented by crowding and acuity in some detail. However, eccentric viewing is also greatly hampered by fixation instability. That is, with increasing distance from the fovea it becomes increasingly difficult for individuals to maintain a lengthy, steady fixation on the relevant stimulus or target.

The issue of fixation stability is a crucial one for perceptual learning studies. Instability means that the target is not bound to any single area of retina, or by extension to any discrete set of neural pathways in the early visual cortex. This could ultimately affect the potential for perceptual learning, at least under bottom-up models.

Given the prevalence of fixation instability in peripheral vision, it is unsurprising that a large 'preferred retinal locus' (PRL) is generally used for fixation under eccentric viewing conditions. As previously noted, a PRL is a discrete area of retina which is habitually used for viewing targets presented peripherally. PRLs are generally larger than the fovea due to the instability associated with eccentric viewing (the image of the target moves across the area bound by the PRL in normal viewing conditions).

Broadly speaking, three types of eye movements occur when fixating with a PRL – microsaccades, drift, and tremor (Møller, Laursen, & Sjølie, 2006). Microsaccades (small-scale, abrupt, and fast eye movements) tend to correct the natural drifting of fixation by moving the target back towards the centre of the PRL. Drift can occur randomly, but about 50% of the drifting movements correct the terminus of an errant microsaccade by guiding the target back to the PRL's midpoint. Generally, the endpoints of these movements do not coincide exactly with the centre of the PRL – it is more common for the intra-drift motion to cross this point. During drifts tremor

also occurs in the movement – extremely small displacements of eye movement that do not alter the average velocity of the drift.

These types of instability are known to affect the performance of visual tasks in the peripheral visual field. Surprisingly, visual acuity and crowding (which are hampered and strengthened by eccentricity, respectively) have been shown to be unaffected by fixation instability (Falkenberg, Rubin, & Bex, 2007). In the same study, reading rate was also shown to be significantly impaired by instability, even when crowding and acuity were controlled for. This suggests that fixation instability may be responsible for the characteristic reading deficits observed in peripheral vision.

A separate study showed that "image slip" (an alternative characterisation of fixation instability) actually increases the effect of crowding, and improves acuity (Macedo, Crossland, & Rubin, 2008). This study used Landolt C's at 5° and 10°; as opposed to upper case letter T's at 4° and 8°, as in the previous study. It is possible that the different stimuli used caused these differences in results – it therefore seems appropriate to reassess letter acuity using a variety of letter stimuli.

Slight instability may be quite beneficial, particularly in peripheral vision. The Troxler effect is a well-known phenomenon whereby extended exposure of an area of retina to a target results in adaptation, and corresponding loss of perception of the target. Instability or jitter have been shown to prevent this adaptation process from occurring (Deruaz et al., 2004). Fixational eye movements of this kind (which prevent the adaptation associated with the Troxler effect) have a clear impact on contrast sensitivity and acuity. They selectively improve discrimination of high spatial frequency stimuli (Rucci, Iovin, Poletti & Santini, 2007) or the contrast sensitivity for high spatial or high temporal frequencies (Kuang, Victor & Rucci, 2012). Simultaneously, contrast sensitivity for low spatial frequencies is reduced (Kuang et al., 2012; Kulikowski, 1971).

Retinal image movements of this kind can also compensate for significant deficits in acuity of the kind observed in peripheral vision (Frisén, 2010), and indeed have also been shown to improve word-recognition speed and facial emotion discrimination in individuals with macular disease (Watson, Strang, Scobie, Love, Seidel & Manahilov, 2012).

These studies characterise the drifting motion observed in PRLs as in some way functional, but other studies have suggested that this type of motion occurs even when no target is present (Whittaker, Budd, & Cummings, 1988). However, this earlier study only considered drifting motion, not saccades. It is possible that both together comprise a functional means of guiding peripheral eye movements.

While it is unclear whether or not fixation instability is in some way functional, we do have some information on the types of stimuli that can affect it. In the early stages of macular degeneration, when central vision is often merely blurred or distorted, various types of fixation aids can be used to promote gaze stability. Pericentral targets (targets that surround the centre) are no better or worse than central targets for people with macular disease, but lead to significantly poorer performance in individuals with normal vision (Bellman, Feely, Crossland, Kabanarou, & Rubin, 2004). A similar study showed that fixation of radial gratings (5° across) is more stable than that of solid discs (0.5°), independent of the visual acuity of the participant (Gonzalez, Teichman, Lillakas, Markowitz, & Steinbach, 2006). The relative sizes of the targets in this latter study may be the key to understanding the data. A 5° radial target is both pericentral and central, and might thus be no worse than a central target. A 0.5° solid disk is potentially too small to be easily fixated by individuals even in the early stages of macular disease.

Unfortunately, central fixation generally becomes impossible once the scotoma has been fully established in central vision. This compounds the issues faced by individuals with macular disease, who must then use discrete

areas of peripheral retina (their PRLs) for fixation without any guidance or assistance from their central vision.

In many cases, individuals with macular disease use multiple PRLs, each appropriate to a different type of task (i.e. reading versus navigation) (Crossland, Crabb, & Rubin, 2011; Crossland, Kabanarou, & Rubin, 2004), but the number of PRLs tends to reduce with time after the development of the scotoma (Crossland, Sims, Galbraith, & Rubin, 2004). Established PRLs tend not to occur above or to the right of the scotoma, and they can often occur in isolated pockets of healthy retina, surrounded by damaged tissue (Fletcher & Schuchard, 1997). PRLs above the scotoma have been shown to be deleterious to reading of blocks of text (Watson, Schuchard, De l'Aune, & Watkins, 2006). As we have noted earlier, reading speed in general is related to fixation stability, but stability itself has been shown to be unrelated to the absolute size of the scotoma (Crossland, Culham, & Rubin, 2004).

Individuals with macular disease can be trained to improve their fixation stability using a variety of techniques. For example, training can establish new PRLs in locations more favourable for reading. In one study individuals with AMD were trained to read scrolled text under high magnification at a novel retinal location (Nilsson, Frennesson, & Nilsson, 2003), leading to significant improvements in reading speed (from 9 to 68 words per minute). Improvements in reading speed, critical print size and fixation stability were also observed in a protocol that trained fixation stability directly, with participants training on a cross, letter, word and radial grating (Tarita-Nistor, Gonzalez, Markowitz, & Steinbach, 2009). Eye movement training can also help to improve reading speed (by 24.7 wpm) (Seiple, Szlyk, McMahon, Pulido, & Fishman, 2005). It is thus clear that fixation stability can be related to peripheral reading ability, though the mechanism itself is unclear.

Despite this, it is promising that the evidence indicates that reading speed can be improved with training. However, a recent review of this area concluded that there is no clear preference between the types of training program used.

Eccentric viewing, oculomotor control, and perceptual learning all contribute to improvements in reading performance (Pijnacker et al., 2011), but without any clear between-condition difference in outcomes. The current study may contribute to our understanding of how best to optimise this type of training.

The literature shows that learning is possible under the unstable conditions found in peripheral vision. Peripheral targets are constantly in motion (to some degree) and position and velocity errors are the main causes of errors in dynamic visual acuity (using Landolt rings) (Brown, 1972a). The current experiment examines letter acuity under a variety of conditions, to examine the impact of different components of fixation instability. For example, we will examine the effect of velocity on letter acuity – previously it has been observed that perception of slowly moving targets can lead to lower thresholds than stationary and quickly moving targets (Brown, 1972b). In contrast to this finding, it has been shown that there is no difference between static and dynamic visual acuity of Gabor patches in the periphery (Lewis, Rosén, Unsbo, & Gustafsson, 2011). Here we examine whether these findings also apply to letter acuity. We will also establish the effect of saccadic motion on letter acuity. It is important to determine how these different types of instability affect the perception of letter-based stimuli in individuals with macular disease. Doing so will allow the development of more efficient training programs that are focused on specific deficits.

It is important to note that the viewing distance in this task is 57cm, as in the previous experiments. A large proportion of reading rehabilitation programs for macular disease focus on reading with high magnification at close viewing distances, which can be poorly tolerated by the individual. The goal of our experiments is to examine the possibility of developing more widely-applicable improvements in peripheral reading ability.

5.2 Methods

5.2.1 Observers

Data was collected from 7 individuals with corrected-to-normal vision. The age of these observers ranged from 18 to 31 years, with a mean age of 24 and a standard deviation of 6 years. Only young observers were recruited, as age does not seem to be related to peripheral fixation ability (Kosnik, Fikre, & Sekuler, 1986) in perception of small targets.

6 of the observers were female, and 1 was male. All observers scored the maximum on the mini-mental state exam (30/30), and no ocular pathologies were reported or detected during screening.

All of the observers in this study were recruited from the School of Psychology's student population.

5.2.2 Stimuli

In all fixation stability tasks, a single upper case letter was presented to the observer in the Arial font. The average position of the letter was centred at 10° above the fixation point, and the letter size was initially set at 3° in height. The target letter was variously set to move or remain static in each of the five conditions in this experiment. The stimuli are described in more detail in the General Methods (chapter 2).

5.2.3 Procedure

Participants were seated with their chin fixed at 57cm from the monitor. One eye was randomly selected to be the viewing eye, and the other was occluded using a patch. Correct responses were indicated by a high-pitched tone and incorrect responses by a lower tone, as in the prior crowding experiment.

The five tasks and the procedure used in this experiment are described in greater detail in the General Methods (chapter 2). Briefly, each of the five tasks measured letter acuity under slightly different conditions, to allow a thorough investigation of the effect of target instability on letter acuity. The five conditions are:

- Static target
    - The target letter remained fixed at 10° above the fixation point.
    - Five stimulus durations were examined.
- Dynamic target
    - The target letter was set with a smooth, continuous motion within a pre-defined region centred at 10° above fixation. If the target reached the border of this region, it was reflected off it with a random heading.
    - Five different drift speeds were used to assess letter acuity at five stimulus durations (see table 2.1).
- Static target with simulated saccades
    - The stimulus characteristics in this task were identical to those in the static target, but for the introduction of simulated saccades at regular intervals.
    - Stimulus duration was constant at 1.49s, but the latency to the first saccade (and frequency of subsequent simulated saccades) varied with five durations.
- Dynamic target with simulated saccades
    - The target letter was set with a smooth, continuous motion as in the dynamic target task, which was regularly interrupted by simulated saccades as in the static-saccading task.
- Dynamic fixation
    - The target letter remained stationary at 10° above the normal fixation point, while the fixation point itself was set with a random drifting motion identical to that used for the target in the “dynamic target” condition.

5.2.4 Data Analysis

Two measurements of letter acuity thresholds were recorded for every condition in each of the five tasks. The standard error was calculated from the responses comprising the final six reversals in each staircase, and averaged across the two staircases.

Bootstrapping was used to help assess the significance of patterns observed in the data.

5.3 Results

In this experiment, participants recorded letter acuity thresholds with five different types of relative target motion (including one condition with no target motion). While fixating on a central cross, letters were presented in the upper peripheral visual field. In order to understand potential effects of target motion in age-related macular degeneration, the effects of stimulus duration, movement speed and saccade latency were assessed. In a related task, the target remained stationary while the fixation cross moved with varying speeds.

5.3.1 Static and dynamic targets

We first assessed the impact of target motion (and the rate of target motion) on letter size thresholds (figure 5.1) using a 2-way ANOVA (duration x speed). There was a significant main effect of stimulus duration ($F(4,20) = 24.84$, $p < 0.0001$), while the effect of target speed approached statistical significance ($F(5,20) = 2.209$, $p = 0.054$). Bonferroni pairwise comparisons did not reveal any specific significant differences between the different group or speed conditions.

We can see in figure 5.1 that the threshold curves for the dynamic / moving targets are consistently higher than those of the static targets, though there were few significant pairwise comparisons for any individual speed condition. Taking the mean static / dynamic values as a whole (figure 5.2), a t-test indicated that static target thresholds are significantly lower than grouped dynamic target thresholds ($t(4) = 7.043$, $p = 0.021$, two-tailed).

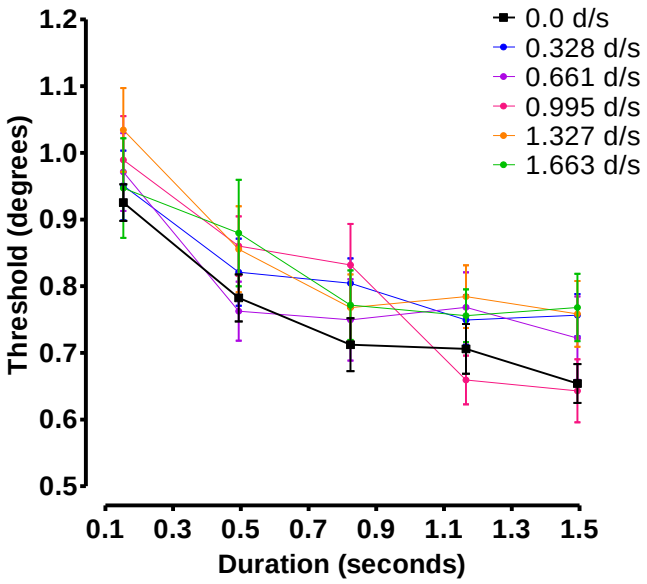

Figure 5.1: Letter size thresholds on the static and dynamic target tasks. Stimulus duration has a strong effect on thresholds, while target speed has a weaker impact. Error bars represent the standard error of the mean.

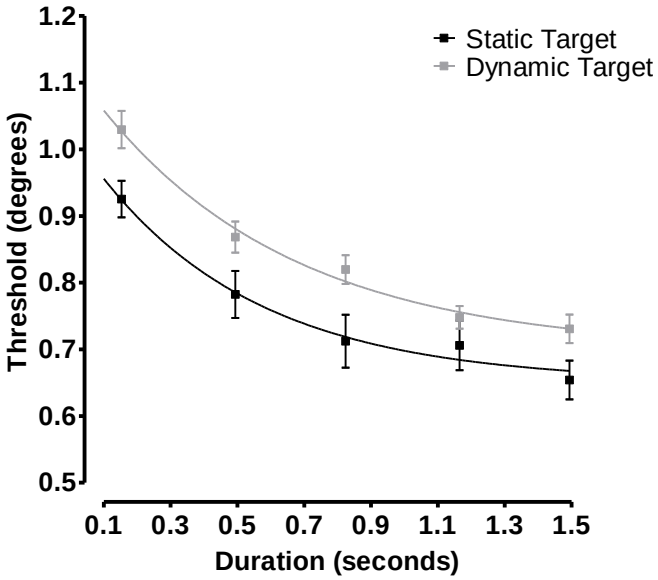

Figure 5.2: Mean letter size thresholds on the static and dynamic target tasks. Target motion significantly increases thresholds on this task. Error bars represent the standard error of the mean.

One-phase exponential decay curves were fitted to these datasets (equations 5.1 and 5.2), with r^2=0.98 for the static data and 0.99 for the dynamic data (Sy.x=0.019 and 0.017, respectively).

$$\text{Static:} \quad y = (1.03 - 0.65) * \exp(-2.08 * x) + 0.65 \tag{5.1}$$

$$\text{Dynamic:} \quad y = (1.13 - 0.69) * \exp(-1.73 * x) + 0.69 \tag{5.2}$$

Comparison of the regressions indicates that one curve cannot be fitted to all of the data in both groups ($F(3,306) = 5.834$, $p = 0.0007$). This suggests that, though similar, static and dynamic acuities show slightly different dependencies on stimulus duration.

However, plotting the data on a threshold/threshold graph we can see that the two datasets are correlated with one another (figure 5.3). A linear regression fits the data well, accounting for the greater part of the variability in the data ($r=0.8145$, $p=0.0021$).

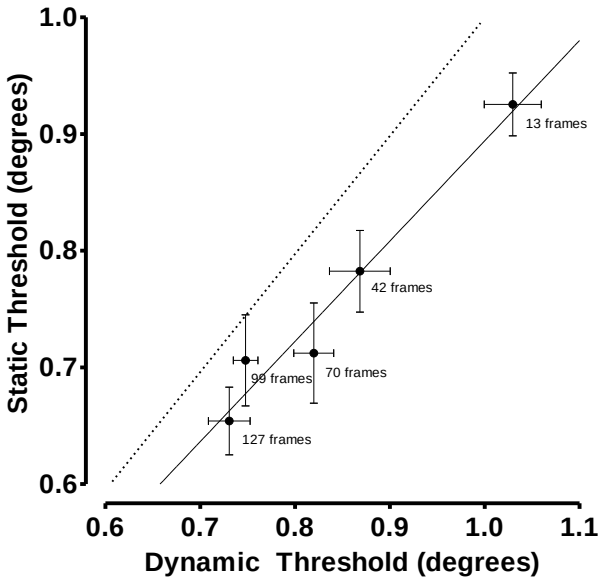

Figure 5.3: The linear relationship between static and (mean) dynamic letter acuity. Error bars represent the standard error of the means for both axes.

Overall, the strong relationship between mean static and mean dynamic letter size thresholds is suggestive of an effect of target motion (rather than

individual speeds) on thresholds. However, it is quite possible that our study was simply underpowered to fully explore this relationship.

5.3.2 Saccades

Having established that target speed could affect letter size thresholds (at least at the speeds selected, and using continuous motion) we next examined the potential effects of simulated saccades. To do so, targets were programmed to 'jump' from one area of the screen to another at selected intervals.

This data is shown in figure 5.4, displayed by the latency to the first (and subsequent) simulated saccade. Stimulus duration remained constant in this condition, meaning that each condition had a different number of simulated saccades – a potential weakness of this experiment.

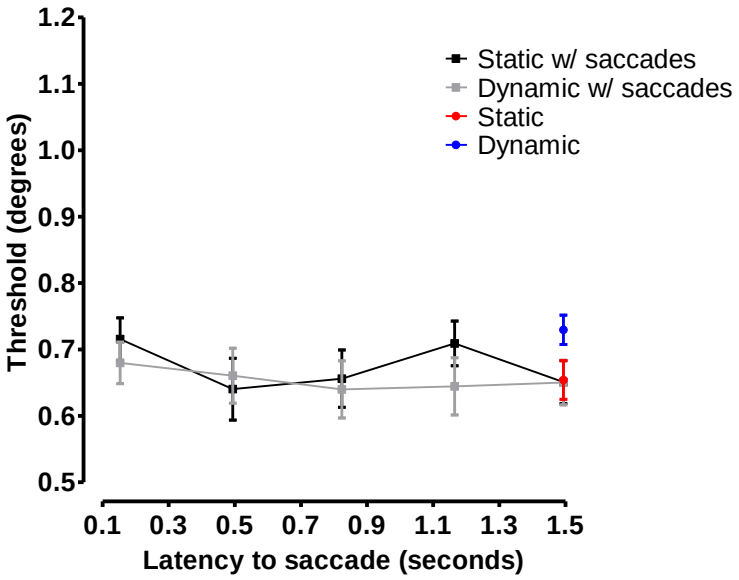

Figure 5.4: Static and dynamic letter acuity thresholds with a (simulated) saccading target. Latency to the first saccade is unrelated to letter size thresholds.

Nonetheless, the data indicates that latency to the first simulated saccade does not appear to affect letter size thresholds on this task. One-way ANOVAs showed no significant effect of latency to the first simulated saccade on static (with simulated saccades) thresholds ($F(4,55) = 0.86$, $p = 0.49$) or dynamic

(with simulated saccades) thresholds ($F(4,55) = 0.17$, $p = 0.95$). A separate t-test of the overall means from these two groups indicated that static/saccading thresholds were not significantly different to dynamic/saccading thresholds ($t(4) = 1.33$, p 0.25, two-tailed).

We also compared the non-saccading versions of these tasks with the saccading version (at the longest stimulus duration). Both comparisons failed to indicate a significant difference between the groups, both for static thresholds ($t(24) = 0.07$, $p = 0.94$, two-tailed) or dynamic thresholds ($t(50) = 1.78$, $p = 0.08$, two-tailed). This latter comparison approaches significance, with the mean for the dynamic/saccading condition (mean = 0.65, SD = 0.12) slightly lower than that of the dynamic condition (mean = 0.73, SD = 0.14).

Thus latency to simulated saccades (and the presence of simulated saccades of any latency) appears to have only a small effect (if any), at least in this experimental setup. The only factors that significantly affect letter size thresholds are stimulus duration (strongly) and target motion (weakly).

5.3.3 Dynamic fixation

In the final condition of this experiment we assessed the impact on letter-size thresholds of a moving fixation point with a static target. Fixation instability in macular degeneration is caused by eye movements, so this experiment was an attempt to model such behaviour.

The data (figure 5.5) shows that thresholds in this dynamic fixation condition are affected by stimulus duration, as in the previous conditions. We used a 2-way ANOVA to assess this data relative to the other conditions. There was a significant main effect for condition ($F(2,375) = 10.6$, $p < 0.0001$) and also for stimulus duration ($F(4,375) = 40.81$, $p < 0.0001$) as previously observed for other conditions. Bonferroni pairwise comparisons indicated that the only significant difference in mean thresholds was between the moving fixation condition and the static target condition at a stimulus duration of 0.153s ($t = 3.259$, $p < 0.01$, two-tailed).

A one-phase exponential decay was fitted to the dynamic fixation data (equation 5.3) (r^2=0.97, Sy.x = 0.045).

$$y = (1.21 - 0.55) * exp(-1.14 * x) + 0.55 \quad (5.3)$$

Comparison of the three curves indicate that a different curve is required for each data set – i.e. the fitted curves are significantly different to one another ($F(6,6) = 8.9$, $p = 0.008$).

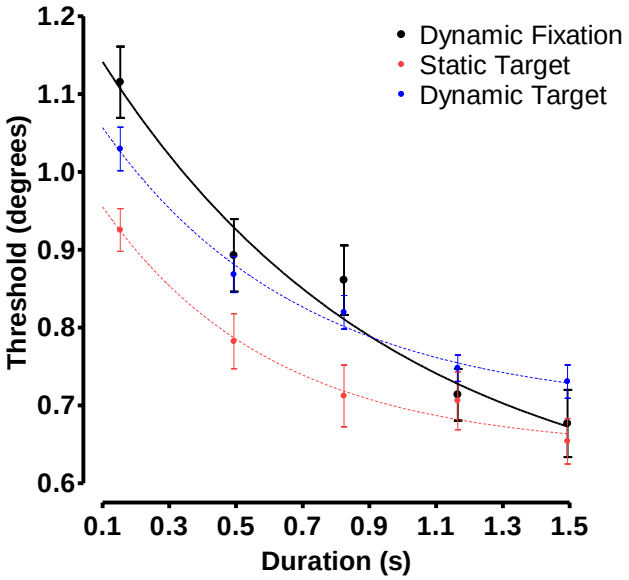

Figure 5.5: Letter size thresholds for a static target viewed while tracking a moving fixation point, as a function of stimulus duration. Error bars represent the standard error of the mean.

5.4 Discussion

This study has demonstrated some interesting features of unstable eccentric viewing. As might be expected from the previous experiments (in particular the word recognition training), longer stimulus durations are associated with a reduction in thresholds (improved performance). This study also shows that target motion (here averaged across several speeds) affects thresholds, though in this case leading to significant increases (worsening performance). This finding is in contrast to similar work in this area. For example, target motion does not appear to affect acuity on an orientation-discrimination task

using Gabor patches (Lewis et al., 2011). However, perception of Gabor patches is known to be highly resistant to positional uncertainty, and it is likely that this resistance led to a lack of an effect of motion in Lewis' study.

Based on the group data, it appears as if motion itself is the primary cause of the reduction in thresholds. Two factors might explain the lack of a relationship with target speed. First, it is possible that our sample size was simply not large enough to detect significant differences between grouped data for specific target speeds. This could be explored with further testing. The other possibility is that our lowest speed (0.328°/s) sets a ceiling for letter acuity on this task. There may yet be a relationship between acuity and target speed for speeds between 0 and 0.328°/s.

A similar lack of effect was observed in the dynamic fixation condition (with a static target). Thresholds here were not significantly different from those of the dynamic target condition. This result suggests that our initial assumption (that a dynamic target is a useful proxy for the sort of dynamic fixation observed in AMD) is at least partly correct.

However, comparing the two curves in figure 5.5 is not necessarily valid. The curve for the dynamic target condition is comprised of several target speeds that have been grouped together. This is therefore not an ideal comparator for the single (fixation point) speed of the dynamic fixation condition.

Nonetheless, our data indicates that the dynamic fixation task led to significantly higher thresholds (at short stimulus duration) than the static target task, but not at longer durations. It is unclear why there might be a complex difference between these two conditions. It may be attributable to an initial cost associated with adjusting to a moving fixation point. Although the fixation cross started at the same point each time, any initial cost to tracking its motion would be reflected in higher thresholds for short-duration trials, just as we observed.

Finally, we reiterate the lack of an effect of saccading targets. This lack of effect is quite interesting, as target recognition in peripheral vision is generally thought to be strongly dependent on deployment of attention (Talgar et al., 2004). A saccading target requires redeployment of attention with each saccade, and thus we expected that it would inhibit performance. The lack of effect suggests that restriction of simulated saccades to a PRL-sized region was sufficient to ameliorate any potential attention-based issues.

5.4.1 Implications

The current study has shown that motion of either the fixation point or the target can reduce the ability of participants to identify letters in the upper visual field. As with the previous experiments in this study, we must bear in mind that the upper visual field is known to be sub-optimal for reading (Watson et al., 2006). Since all of our tasks are set in this area, comparing performances and results across each experiment is permissible. In future, we must still consider the impact of this factor on the development of any training or rehabilitation programs, for which these findings may need to be verified in more usable parts of the visual field.

That proviso aside, these results present an interesting comparison to what we know about the Troxler effect. Studies in this area normally use a form of target 'jitter' rather than full motion to ameliorate the effects characteristic of Troxler adaptation. In the former case, jitter can worsen reading rate without affecting acuity (Falkenberg et al., 2007) or it can improve acuity (Macedo et al., 2008) depending on the specific stimulus and protocol used.

In the current study, target motion served to increase letter-size thresholds, in contrast to these previous studies. This indicates that motion on the scale used here is disruptive for letter perception, and that this disruption is greater than any benefit derived from eliminating adaptation.

There are several methodological issues with this task that should be taken into account if its findings are to be integrated into the wider study. First, given the freedom of the target or fixation point to range over a fixed area of

the visual field, it is clear that responses from a range of eccentricities are being conflated. Increased eccentricity will make some trials on this task more difficult, as it is linked to an increased cognitive load on the observer, reductions in acuity and image resolution, and increases in positional uncertainty.

We have assumed that targets further from fixation will be counterbalanced by those closer to fixation. The letters used in the task were also relatively large at 3°, particularly as compared to the size of the circle (2.297° ^{2}) within which the letter's centre could move. Small changes in eccentricity, as used in this task, do not necessarily lead to undue increases in fixation instability (eccentricity was shown to be unrelated to fixation stability by Greenstein et al., 2008). Despite this, the variations in eccentricity remain a potential source of confounds in this data.

Further to this, we note that the types of motion used in our programs do not exactly match those observed in individuals with macular disease. In particular, saccades for the latter group are generally oriented towards the target as a form of 'course correction'. Bearing in mind that the simulated saccades in our program did not appear to have any effect on thresholds, we suggest that more natural saccades (that presumably would improve perception) would also be unlikely to have had a significant effect on thresholds.

5.4.2 Conclusions

Despite its weaknesses, the current study has demonstrated that a simple increase in duration can dramatically improve letter-size thresholds for dynamic or static targets. It also suggests that letter-identification thresholds could be equated across static and dynamic conditions, simply by increasing the stimulus duration of either type of dynamic condition. The differences between conditions are not large (and are small compared to the effects of stimulus duration) and thus may be amenable to training.

Individuals with unstable fixation can be trained to improve their stability (as well as associated outputs such as critical print size and reading speed, see Tarita Nistor et al., 2009), for which a variety of methods have been employed. However, there is currently no consensus on the optimal type of training (Pijnacker et al., 2011). This data shows that relative target motion across the retina (whether caused by motion of the target or fixation point) leads to increases in letter-size thresholds (just as it does with reading speed). This effect is small, and the threshold/duration curves are very similar across conditions, suggesting that similar processes are involved. We can thus be confident that our training protocols are unlikely to be qualitatively affected by fixation instability – the effect, rather, may simply be comprised of a quantitative reduction in pre- and post-training thresholds.

Knowing that this task is affected by target motion, it will be instructive to observe how (or if) perceptual learning is affected in a sample with macular disease, for whom target motion is likely due to poorer fixation stability. We will go on to look at this issue in the next chapter.

Chapter 6: Perceptual learning in individuals with AMD

6.1 Introduction

We have seen previously that significant improvements in word recognition speed are achievable in an older sample of normally-sighted individuals. Post-training thresholds are largely dependent on the age of the individual participant, with older participants showing less improvement for a given number of training sessions. Once this is taken into account (by providing further training sessions to older participants), then final thresholds are broadly similar across all ages.

This finding is vitally important for the next phase of this study, where we train individuals with age-related macular disease on a similar word recognition task. We assume that any significant differences from the baseline observed in the previous study will be due to the effect of the participants' AMD, rather than age. As previously noted, peripheral vision is generally affected by acuity deficits, increased crowding (Pelli et al., 2007), decreased contrast sensitivity (Chung, Levi, & Li, 2006), and increased fixation instability (Gonzalez, Teichman, Lillakas, Markowitz, & Steinbach, 2006). We have corrected for acuity deficits, and from our previous experiments we now know a little more about how performance might be affected by the increased crowding and fixation instability. If we ultimately find that our sample with AMD can perform comparably to the normally sighted sample, then we can have greater confidence that this training protocol is effective irrespective of both age and the presence of AMD.

Previous studies have also revealed a great deal about reading / letter identification in AMD. Reading speed is known to be affected by a number of variables in individuals with AMD. For example, scotoma size in itself has a negative impact (Cummings, Whittaker, Watson & Budd, 1985) as does fixation stability (Crossland, Culham, et al., 2004). Similarly, near word acuity and scotoma size combined have been observed to contribute to up to 60% of

the variance in reading speed (Cacho, Dickinson, Smith & Harper, 2010). It has also been reported that visual span size and information transfer rate are impaired in AMD participants (Cheong, Legge, et al., 2008). In this study it was reported that information transfer rate (the combined effect of reduced visual span size and slower letter-processing) was a good predictor of reading speed.

All of these factors are potential targets in rehabilitating individuals with AMD. Apart from scotoma size, they are all amenable to improvements, but it is unclear if such improvements would automatically lead to an improvement in reading speed.

For example, crowding is known to inhibit reading speed in individuals with normal vision, but Chung (2007) reports that learning to identify crowded letters does not lead to improvements in reading speed. The same study also reports the (somewhat counterintuitive) finding that improvements in letter acuity also have little effect on reading speed. Similarly, increasing the line spacing in passages of text (or increasing the vertical separation between words presented in RSVP) also has no effect on reading speed in participants with macular disease (Chung, Jarvis, et al., 2008).

Reviews of interventions that have an effect on reading speed in an AMD population have been inconclusive. In a recent review (Seiple, Grant, et al., 2011), eye-movement control was suggested as a useful target for intervention (see also an original study by the same principal author: Seiple, Szlyk, et al., 2005). However, the authors note that other interventions also have value, while perhaps lacking the efficiency of their own method. In the same year, a broader review of training methods (including eccentric viewing, eye-movement control, and perceptual learning) indicated that no individual method was unequivocally superior to the others (Pijnacker et al., 2011).

Our own efforts, reported here, have shown that we can induce improvements in word recognition speed in a sample of normally sighted individuals. What is clear from the preceding paragraphs is that we must ensure that these improvements:

- Are replicable in a sample of participants with AMD, and
- Lead to behaviourally useful improvements for our participants.

The latter point is no small issue. We know that clinical measures of visual function do not necessarily transfer to behaviourally significant improvements for participants (Dubuc, Wittich, et al., 2009). At the very least, any such improvements are not always apparent to the individual participant.

We thus felt that it was important, in this part of our program of research, to demonstrate a more behaviourally relevant measure of improvements. To this end, we used the MNRead acuity chart, a simple tool that allows us to measure reading acuity, maximum reading speed (in words per minute) and the critical print size for reading. The task involves reading individual ten-word sentences presented in mini-paragraphs (see Figure 6.1 for an example), and is thus more similar to everyday reading than the word recognition task.

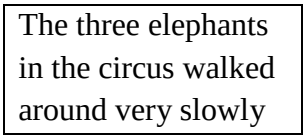

Figure 6.1: Sample trial from the MNRead acuity chart.

The presentation of the sentences on the MNRead chart tends to make them more difficult to perceive than on our word recognition task. We know that crowding is increased by flankers that are more peripheral than the target (Bouma, 1970), which is compounded by the fact that crowding fields are generally larger in the radial than tangential directions (Toet & Levi, 1992). The words comprising the MNRead sentences can thus be expected to be crowded from all four directions, and crowded variably within each sentence (as the middle line will have greater radial crowding than the upper and lower lines).

We expect that training on the word recognition task will induce improvements in word recognition speed in our sample of participants with AMD. Despite the potentially greater difficulty of the MNRead task, we also

expect to observe improvements in reading speed on this task (measured through testing before and after the word recognition training).

6.2 Methods

6.2.1 Observers

Data was collected from 5 individuals with age-related macular disease. Further characteristics can be seen in Table 6.1.

The age of these observers ranged from 67 to 81 years, with a mean age of 76 and a standard deviation of 6 years. 3 of the observers were female, and 2 were male. All observers scored within the normal range on the mini-mental state exam (mean value = 29).

All of the observers in this study were recruited via the University of the 3rd Age and the Macular Disease Society.

	Gender	Age	AMD Type	Diagnosed	Training site
MD1	F	80	Wet, Bino	1994	Left eye, upper
MD2	F	81	Dry, Mono	1999	Right eye, lower
MD3	F	75	Dry, Mono	2002	Left eye, upper
MD4	M	67	Dry, Mono	2009	Right eye, lower
MD5	M	76	Dry, Mono	2008	Right eye, upper

Table 6.1: Visual characteristics of observers

6.2.2 Stimuli

Training was delivered with an adapted version of the word recognition task (see section 2.5.7). The main difference between this and previous versions is that the fixation point was replaced by a large diagonal cross, which extended 9.1° above and below fixation and 11.1° to the left and right (figure 2.12). It thus attempts to ensure that even individuals with large scotomas would be able to guide their eye movements towards the fixation point, similar to the manner in which large radial gratings have been shown to improve fixation stability in previous studies (Gonzalez, Teichmann, et al., 2006). Stimulus duration had no set upper limit in this study.

Participants were screened for cognitive decline using the Mini-Mental State exam. The eye chosen for macular observers was based on data obtained from the Amsler grid (Amsler, 1953) and from perimetry testing using the Humphrey Visual Field Analyser (Carl Zeiss Ltd, UK). The latter uses simple threshold tests to detect defects in the sensitivity of the eye at a wide range of eccentricities. See chapter 2 for further details on the protocol used.

6.2.3 Procedure

Participants began with a standard visual acuity test (using a wall-mounted chart), followed by a screening for cognitive decline using the Mini-Mental State Exam.

The extent of visual loss in the eye with macular disease was then mapped using the Humphrey Visual Field Analyser. These maps allowed us to choose the eye to be trained (in the participant with binocular macular disease) and the site of training (above or below fixation). The criterion used was the availability of working retina at the required training location.

Once the appropriate eye had been chosen, reading acuity, critical print size and maximum reading speed were assessed using the MNRead acuity chart (Mansfield, Ahn, Legge, & Luebker, 1993), based on the instructions supplied by the manufacturer. This assessment can be carried out at a variety of viewing distances based on the visual ability of the observer, with corrections made to the results based on this distance.

For the word recognition training, participants were seated with their chin fixed at 57cm from the monitor. The training eye was corrected for the viewing distance, and the other was occluded using a patch. Responses were corrected or confirmed by the experimenter, who read out the correct response after each trial.

All participants had fifteen training sessions, inclusive of the pre- and post-session. The final session was followed by a second assessment with the MNRead acuity chart.

6.2.4 Data Analysis

Word recognition data was assessed as in the initial study – see section 3.2.4. Outputs from the Humphrey Visual Field Analyser were used to determine the optimal viewing site, as described in chapter 2. Outputs from the MNRead acuity chart were calculated using the instructions provided.

A bootstrapping program in Matlab was used to assist in assessing the significance of any potential patterns in the data.

6.3 Results

In this experiment, we sought to determine if individuals with AMD could achieve improvements in word recognition speed similar to those of age-matched normally sighted individuals. To this end, five participants with AMD were trained on the word recognition task for fifteen days. They were screened and pre-tested with an Amsler grid, visual acuity assessment, MNRead acuity chart and mini mental state examination. They were also assessed on the MNRead acuity chart in a post-training phase. The latter was used to establish if there was any potential transfer of learning from the word recognition to a more natural reading condition.

6.3.1 Word recognition

Thresholds for the AMD group improved over the course of training (figure 6.2). There was a significant difference between mean thresholds on day 1 (mean = 2.66, SD = 0.14) and day 15 (mean = 0.69, SD = 0.16) ($t(8) = 20.72$, $p < 0.0001$, two-tailed).

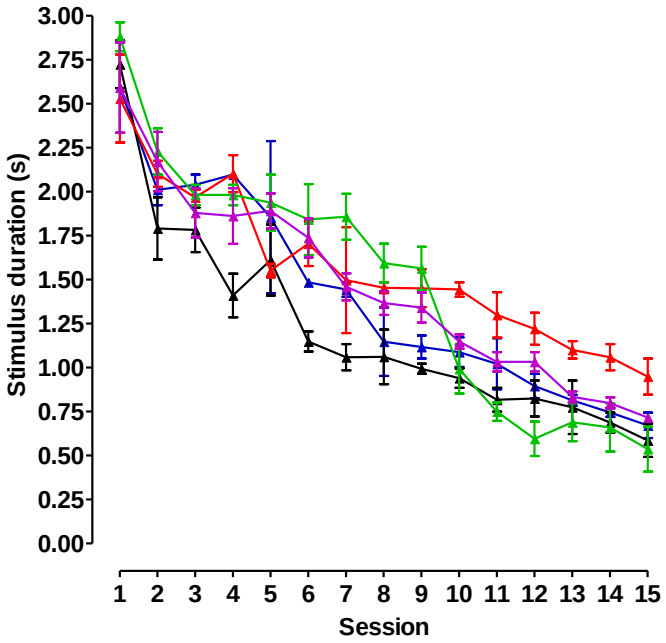

Figure 6.2: Training stimulus duration thresholds on the word recognition task in five participants with AMD. Error bars represent the standard error of the mean.

We also sought to compare thresholds from this group to those of our other groups. In doing so it was important to match the conditions as closely as possible. The AMD group's version of the word recognition task did not have an artificial ceiling imposed on stimulus duration, unlike the majority of previous participants. Therefore we chose to use as a comparison group the participants who had trained on a version of the task with no artificial ceiling (see page 89, figure 3.12) (n = 5, mean age = 63.5, SD = 5.6). Thresholds for these two groups can be seen in figure 6.3.

Using a 2-way repeated measures ANOVA to compare these two groups, we observed a significant main effect of 'session' ($F(9,72) = 63.24$, $p < 0.0001$) and a significant interaction ($F(9,72) = 2.6$, $p = 0.12$). The effect of 'group' was non-significant ($F(1,72) = 2.22$, $p = 0.17$). Bonferroni pairwise comparisons between the groups for each session indicated no significant differences between the means.

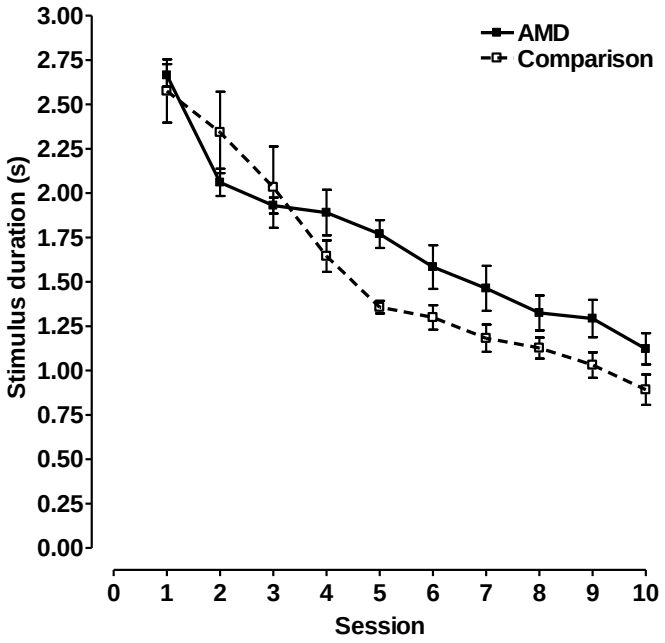

Figure 6.3: Mean training stimulus duration thresholds on the word recognition task for the AMD group and a comparison group of a similar (but not fully matched) age. There was no significant difference between the groups. Error bars represent the standard error of the mean.

These results indicate that macular disease does not necessarily inhibit perceptual learning on this visual task. However, our comparison group only trained for 10 sessions, and the AMD group trained for 15 sessions. In order to assess the changes in threshold by the end of training, we also compared the means of the AMD group to:

- Day 10 thresholds for our original younger group (n = 12, mean age = 32.5, SD = 11.1),
- Day 15 thresholds for our extended-learning group (n = 5, mean age = 63, SD = 6),
- Post-test thresholds for the control group (n = 10, mean age = 38.1, SD = 19.6).

The comparisons were made using raw thresholds, as the artificial ceiling limiting initial task performance could distort PPR data. A one-way ANOVA indicated a main effect of group ($F(3,27) = 33.12$, $p < 0.0001$). Bonferroni pairwise comparisons indicated statistically significant differences only between the control group and each of the other three groups. Of interest in

this comparison, the comparison of AMD (mean = 0.69, SD = 0.16) and control groups (mean = 1.29, SD = 0.17) was highly significant ($t = 5.06$, $p < 0.001$, two-tailed). The pairwise comparison between the AMD group and the younger group (mean = 0.41, SD = 0.26) was non-significant ($t = 2.50$, $p > 0.05$), as was the comparison with the extended-learning older group (mean = 0.44, SD = 0.21) ($t = 1.84$, $p > 0.05$).

Although the mean of the post-test thresholds were numerically higher (albeit not significantly) in the AMD group, our results have established that these observers are capable of significant improvements on the word recognition task.

6.3.2 MNRead

At the post-test, we also examined performance on the MNRead acuity chart. Pre- and post-training scores are shown in table 6.2 and figure 6.4.

	Reading Acty (logMAR)		**Critical Print Size (logMAR)**		**Max Reading Spd (words per min.)**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
AMD1	1.16	0.98	1.20	1.20	12.00	15.00
AMD2	1.32	1.20	1.30	1.30	4.00	8.30
AMD3	1.00	0.68	1.20	1.20	66.60	75.00
AMD4	0.90	0.65	1.10	1.00	60.00	75.00
AMD5	1.00	0.80	1.10	1.10	35.70	55.00
Mean	1.08	0.86	1.18	1.16	35.66	45.66
Standard Dev.	0.17	0.23	0.08	0.11	27.89	32.19

Table 6.2: Pre- and post-training scores from the MNRead acuity chart.

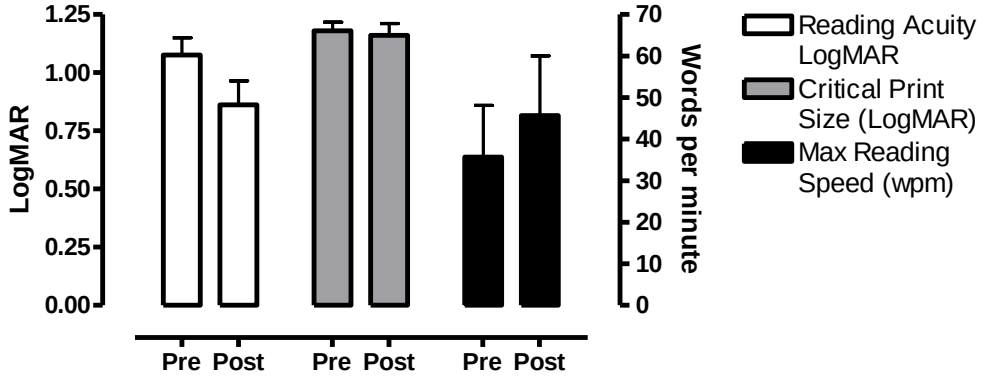

Figure 6.4: Mean pre- and post-training scores on the MNRead acuity chart. Error bars represent the standard error of the mean.

Repeated measures t-tests (two-tailed) indicated that changes in reading acuity and maximum reading speed were significant (see table 6.3), but no statistically significant difference was observed between pre- and post-training scores for critical print size.

	Mean difference (Standard deviation)	**t-statistic**	**df**	**Sig. (p-value)**
Reading Acuity (logMAR)	0.214 (0.08)	6.35	4	0.003**
Critical Print Size (logMAR)	0.02 (0.07)	1.00	4	0.374
Max Reading Speed (words per min.)	-10 (7)	3.20	4	0.033*

Table 6.3: Mean and standard deviation of the change in MNRead scores before and after training. T-statistics and p=values indicate that the changes in reading acuity and maximum reading speed are significant.

These changes suggest that some between-task learning has occurred. Specifically, improvements on the word recognition task have led to improvements in generalised reading performance, as assessed by the MNRead acuity chart.

6.4 Discussion

This study has demonstrated that initial performance and learned improvements on the word recognition task are not specifically limited by age-related macular disease. Our small sample of observers with AMD recorded pre- and post-training thresholds that were not significantly different to comparison groups of younger and older observers.

However, post-test thresholds for the AMD group were still higher than those of the younger and older comparison groups (by 69% and 56%, respectively), suggesting that further improvements in threshold may be possible. Increasing the number of training sessions (which facilitated additional improvements in our original older group of participants) may also help to drive further improvements in an AMD group. Fatigue may also have been an issue, and could perhaps be offset by more gaps between training sessions. Alternatively, the differences observed may be an artefact of our small sample sizes. Nonetheless, the reduction in thresholds observed for the AMD group remains an interesting finding, and suggests that perceptual learning mechanisms remain intact in this population.

Having established that significant perceptual learning has taken place in our sample, we can turn to what was the primary motivation for these studies – an exploration of the potential rehabilitation of individuals with AMD. With that in mind, we were initially encouraged to observe between task learning on two out of three outputs of the MNRead acuity chart (i.e. reading acuity and maximum reading speed). No change was observed in critical print size.

The fact that improvements were not observed in critical print size is not altogether surprising. This is operationally defined as the smallest print size that can be read with the observer's maximum reading speed[1]. The word recognition task required our participants to interpret on-screen stimuli with of unchanging size and diminishing durations. Size was not an issue in this

[1] Maximum reading speed is defined as the reading speed recorded when print size is not a limiting factor.

task, so we would not necessarily have expected to observe improvements in critical print size.

One potential flaw in our approach was the lack of a control condition for the MNRead acuity chart. Several studies have examined the test-retest reliability of this task, with varying results. One previous study (Subramanian & Pardhan, 2006) tested 30 students on the MNRead chart (mean age = 23.3, SD = 3.6), and repeated the test after a "small break". Test/retest variability was reported as a Coefficient of Repeatability (CR) for each task (table 6.4). The CR is the value below which the absolute difference between test and retest scores would be expected to be found with a probability of 95%. As the differences recorded in our study are above these values, we believe that the changes observed are unlikely to have resulted simply from repeating the MNRead test alone.

	Mean change	**Repeatability coefficient, Subramanian et al. (2006)**	**Repeatability coefficient, Subramanian et al. (2009)**	**Repeatability coefficient, Patel et al. (2011)**
Reading Acty (logMAR)	-0.214	0.05	0.1	0.3
Critical Print Size (logMAR)	0.0	0.12	0.2	0.44-0.67
Max Reading Spd (words per min.)	10	8.6	10	66-94

Table 6.4: Mean changes in MNRead scores before and after training from the current study, alongside the coefficient of repeatability from three previous studies.

However, more recent studies have also reported on the repeatability of the MNRead task, but with a much broader range of repeatability coefficients. Subramanian reports slightly higher coefficients in a later study (Subramanian & Pardhan, 2009), and on the basis of these results we would also remain confident in the effectiveness of our intervention. However, a later study by Patel (Patel, Chen, da Cruz, Rubin & Tufail, 2011) reported significantly higher coefficients for each measure. This study differed from ours in two important

respects. First, their observers were all in the early stages of macular degeneration. Second, assessments were carried out in a busy clinical (non-laboratory) setting, alongside a wide range of other assessments (administered by separate individual professionals). Fatigue and the intrusion of uncontrolled factors may thus have been an issue. That said, we should bear in mind that the reliability of the MNRread task is in question, and should be considered in future studies.

The transfer of learning to the MNRead task has a second interesting aspect to it. Participants were trained on a crowded word recognition task, and also improved their responses on a more crowded (and more complex) sentence reading task. As previously noted, crowding tends to be strengthened when the target has flankers that are more peripheral than it (Bouma, 1970), and radial crowding fields are usually larger than tangential fields (Toet & Levi, 1992). The practical effect of this is that a participant attempting to identify any individual word in a sentence on the MNRead chart would experience crowding tangentially (much as in the word recognition task) but also radially (though it seems likely that increasing the spacing between lines would not have improved performances – see Chung, et al. (2008)). Even though the strength of this crowding would vary within the sentence (e.g. the upper right-most word would only be crowded from the left and below), we would still expect that the strength of crowding would continue to have a detrimental effect on thresholds. The observed ability to improve participants' thresholds on this task is therefore extremely promising.

However, we remain unclear as to exactly how this effect occurred. Some factors can be ruled out. For example, Chung (2007) reported that participants who had learned to identify crowded letters did not improve their reading speed. It thus seems plausible to suggest that simple alleviation of crowding did not lead to the observed effects. We also know (from our previous study, reported in chapter 4) that crowding is age-independent, so we might expect to have observed the same results in a younger sample.

One unique characteristic of this training protocol was the use of a large diagonal cross instead of a fixation point (designed to allow individuals with central scotomas to maintain fixation). Large radial gratings have previously been shown to improve fixation stability (Gonzalez, Teichmann, et al., 2006), and this may have contributed to some of the effects observed. Improved eye movement control has previously been found to lead to improvements in participants with AMD (Seiple et al., 2005), so this may have contributed to our results. It would be interesting to train a normally sighted sample on this altered version of the word recognition task to determine if it does lead to greater training effects.

6.4.2 Conclusions

A wide array of training protocols have been employed to address the deficits inherent in age-related macular disease, with no clear consensus on the superiority of any given method (Pijnacker et al., 2011).Our data lends support to a perceptual learning approach, making use of crowded, short-duration stimuli. A further important aspect of the current study is the use of appropriate correction for visual acuity deficits, and the use of a carefully selected training site. All of these factors may be important contributors to a training program with wider applications. In particular, great care should also be taken in selection of a training site. We have used a site above the scotoma, but PRLs above the scotoma have been shown to hamper reading of blocks of text (Watson, et al. 2006). It would be useful to study similar techniques at other points in the visual field in future.

Finally, we would again stress the importance of developing a training program that leads to behaviourally significant improvements for the participants involved. Clinical measures of visual function, while intrinsically interesting, may not have wider application, so we should always seek to ensure the relevance of any outcomes from new protocols.

Chapter 7: Discussion

7.1 Background

Over the course of these experiments, we have sought to gain a greater understanding of peripheral visual perception, with a particular focus on letter identification and word recognition. This work is intended to help develop a wider understanding of the nature of visual processing in general, but it is also interesting in that it has potential use in ameliorating the effects of visual disorders such as age-related macular disease (AMD).

Age-related macular disease is a visual disorder that ultimately results in significant, often debilitating loss of central vision (Geruschat et al., 2010; Midena et al., 1997; Pijnacker et al., 2011). Specifically, it is the macula itself (the most sensitive part of the retina) that is damaged in either of the main forms of this disease (neo-vascular and geographic atrophy), leading to significant deficits in visual acuity, contrast discrimination, face recognition, reading, etc. (Owsley, 2011).

Though many risk factors exist, the single biggest risk factor is age itself, with the majority of cases occurring in individuals over 50. We might thus assume that, in the absence of novel treatments or preventative therapies (particularly for geographic atrophy / dry AMD), the significance of this disease will increase for wider society as the population ages.

In the course of the studies described here, we have frequently used normally sighted individuals as a model for individuals with macular disease. We have chosen to do this because it seems likely that normal peripheral vision shares much in common with the peripheral vision of individuals with macular disease. For example, both are affected by reductions in acuity and contrast sensitivity (Chung et al., 2006) , an increase in visual crowding (Pelli et al., 2007) and significant fixation instability (Gonzalez et al., 2006). We therefore hypothesised that any effects or trained improvements we observed in a

normally sighted sample would be possible to replicate in a sample of individuals with macular disease.

In the key studies of this research we have used perceptual learning as our primary technique. Perceptual learning refers to relatively long-lasting changes in sensory function induced by experience of any kind, whether through deliberate training or natural sensory experience (Gibson, 1969; Sagi, 2011). The mechanisms of perceptual learning remain somewhat unclear, but as with all types of learning a balance must be struck between specificity and generalisation. Training on a highly specific set of simple stimuli (often thought to induce changes in the early processing stages of visual cortex) is less likely to have broad application outside the specific, trained context. Conversely, more general training (which may recruit a wider neural network, and target later processing stages in cortex (Levi & Li, 2009)) may lead to more generalisable learning.

The tasks used in this research generally lie somewhere between these two extremes. Where we are interested in the broader implications of learned improvements, we have tended to opt for higher-level tasks. On the other hand, where our interest was in exploring a particular issue in detail (e.g. crowding) we have preferred to use simpler stimuli. The first, and largest, set of experiments in this program used a selection of such tasks to explore the relationship between age and perceptual learning of peripherally located visual stimuli.

7.2 Perceptual learning in the peripheral visual field

We have known for some time that the developing brain is capable of extraordinary plasticity, but it has previously been thought that the mature adult brain was incapable of the sorts of changes observed in the early stages of development. We now know that working-age adults are also capable of a plastic neural response (Dinse, 2006; Mahncke et al., 2006), but evidence for behaviourally significant neural plasticity in older adults has been weaker. This

first phased of our study was partly motivated by an attempt to further explore this issue.

Three tasks (word recognition, contrast sensitivity and three-dot bisection) were developed, and individuals from across the age-range were randomly assigned to train on one of them. The results from this study were striking. Taken as a whole, our participants demonstrated improvements on both the contrast (mean PPR=0.46, SD=0.26) and word recognition (mean PPR=0.4, SD=0.26) tasks, though given equivalent training younger adults achieved lower thresholds than the older groups. Overall, this indicates that significant perceptual learning is possible in the peripheral visual field at every age.

When studying visual perception in older adults, certain challenges are apparent. Apart from the well-documented visual deficits, we know that declines in memory and processing speed are widespread for this population (Mahncke et al., 2006). Previous studies have shown that older adults can achieve significant visual perceptual learning, e.g. (Yu et al., 2010), so it is promising that such improvements were also demonstrated in the current study.

No improvements were noted in the bisection task – see chapter 3 for details on why this is likely to have occurred. However, significant improvements were reported on each of the other two studies.

On the contrast task, the group as a whole recorded a significant improvement in thresholds. This change in thresholds was significantly greater than that observed in the control group, though this was not the case for a comparison of PPRs.

Contrast sensitivity is known to be affected by age (Crassini et al., 1988; Jackson & Owsley, 2003; Owsley et al., 1983), but the size of the difference in contrast sensitivity between old and young is generally quite small (Owsley, 2011). Our data reflects this, but the difference (between young and old groups) in thresholds was nonetheless significant at the pre-training session.

Thresholds were correlated with age and were significantly higher for older participants. This effect was no longer present at the post-training session, though this may be attributable to the smaller post-training sample.

For the word recognition task, our younger participants achieved lower thresholds than older participants, a pattern that can also be observed in reading of full RSVP sentences (Levi et al., 2007; Yu et al., 2010; Chung, 2011). Previously, suggestions to overcome age-related differences in performance have included the use of additional training sessions (Richards et al., 2006), which is also the approach we have used here.

By the 10th day of training, our older participants had thresholds that were significantly higher than those of the younger participants. We therefore opted to train a sub-sample of older participants for a further 5 sessions, which allowed the older participants to match the day 10 thresholds of the younger participants. This effect, whereby thresholds recorded by older observers 'catch up' with those of younger observers, has been previously observed in a motion discrimination task (Ball & Sekuler, 1986). It leads us to believe that there are no (or limited) qualitative differences in learning ability between old and young, at least on this task.

Equally promising is our observation that the improvements in thresholds were largely maintained (for all ages) at a retest 6 months after training. Previously, maintenance of threshold improvements for amblyopes has been observed at 12 months (Zhou et al., 2006), so this finding was not unexpected. In our study, thresholds did worsen over the course of 6 months, and older individuals showed greater relative losses. However, those older observers who received extra training sessions reduced their losses equivalent to those of younger observers. Retention of learning after such a long period suggests that significant perceptual plasticity can be usefully retained in the aging visual system.

Overall, the results of this first phase of testing were quite promising, and resulted in the highly significant finding that improvements in thresholds could be equalised between older and younger observers.

7.3 Crowding

The next component of our research was in part influenced by a desire to investigate the differences in thresholds observed on the perceptual learning protocols. Older observers recorded higher initial thresholds on our word recognition task, and one possible explanation for this was an increase in crowding with age.

Declines in many aspects of visual processing are known to be linked to increasing age. Memory and processing speed decline almost universally (Mahncke et al., 2006), but increases in visual crowding have also been reported (Scialfa et al., 2013). This should have a clear effect on our studies in particular, and crowding has (as previously noted) a significant impact on peripheral visual perception in general. We therefore sought to further explore any interaction between ageing and this phenomenon.

In this study, we used established psychophysical methods (Hussain et al., 2012) to characterise the effect of age on visual crowding in a letter identification task. Letter identification thresholds and the spatial extent of crowding were recorded. Uncrowded / crowded visual acuity and spacing thresholds were expressed as a function of age, which helped us to avoid the binary categorisation of young/old used in our other studies.

Our results showed that uncrowded and crowded visual acuity do not appear to be related to age. Spacing thresholds were also age invariant, and approximated Bouma's law (half eccentricity), as expected.

These findings differ from Scialfa's study (2013) which observed poorer crowded visual acuity in older participants. However, that study also showed that the crowding ratio did not change with age, and failed to explore the

spatial extent of crowding, which is a better index of crowding effects in general.

The age-independent stability of the effect of crowding on single letter recognition that we observed may have been facilitated by a number of factors. Our study utilised optical correction, which helped to alleviate any confounding acuity deficits. We also demonstrated that the key variable affecting thresholds in this task was letter spacing, which is already well known to affect both word and letter recognition (Chung, 2002).

The key influence of spacing may also have some bearing on the differing patterns of results observed in letter recognition, word recognition and RSVP sentence reading studies. Use of letter spacing sufficient for fluent letter recognition may require words to occupy quite a broad span across the visual field. In general, words can be scaled across eccentricity to equate word recognition thresholds (Latham & Whitaker, 1996), so this is not necessarily a problem for word recognition itself. However, the same cannot be done to improve RSVP sentence reading. This point of difference remains unclear. However, RSVP sentence reading requires consistent redeployment of attention to different parts of the peripheral visual field, which may impair performance.

There are two other key issues that our results relate to. First, we saw in the Introduction chapter that crowding is often conceptualised as being the result of erroneous feature integration at some stage in the visual processing pathway. If this is the case, our current data heavily implies that feature integration is also a mechanism that we would expect to be preserved into senescence. Related to this, our results indicate that crowding and surround suppression (also theorised to be a result of faulty feature integration) can be differentiated. Surround suppression is known to be affected by age, so our data suggests that the mechanisms responsible for these two phenomena are quite different.

Overall, this part of our set of experiments has left us with a 'null' result – there is no relationship between visual crowding and age. However, in the context of our wider plans (and the broader motivation behind these studies) this is a very positive result. It is another reason to believe that data from our younger participants is directly comparable to that from our older participants. It also eliminates a confounding variable from these studies that, a priori, we might have expected to have a large influence. With this in mind, we now turn to another visual phenomenon that we also believe may affect perceptual learning of these tasks – fixation instability.

7.4 Fixation

The experiments described thus far have all relied on normally sighted observers viewing peripheral targets while fixating on a central point. In these conditions eye movements would be expected to be minimised. All of this data has thus been recorded under conditions in which fixation stability is not an issue.

Unfortunately, individuals with macular disease suffer from strong instability of fixation. It was unclear how or if this would affect performance on these tasks. In particular, it was unclear whether or not this would affect the ability of individuals with macular disease to exhibit the sort of robust perceptual learning we have previously observed.

With that in mind we devised a series of studies that tested the effect of fixation instability (here defined variously as either a moving target or moving fixation point – see chapters 2 and 5 for further details) on letter recognition. Motion of either the fixation point or the target was shown to reduce letter identification thresholds in each condition, though there was no consistent effect for the individual target-speed conditions. However, the strongest predictor of performance was stimulus duration, with simple increases in duration leading to dramatically improved thresholds. We also observed that thresholds in the dynamic conditions could be equated with those in the static

condition merely by increasing the stimulus duration, suggesting that the observed differences between conditions may be amenable to training.

In this study, target motion impaired letter identification. Previous work on the Troxler effect has used jitter/target motion to improve task performance, particularly for high spatial frequency targets. Improvements in threshold might also be expected under models whereby instability serves a functional value (Frisen, 2010), though in these cases the instability is generally not on the same scale as the motion simulated in our study.

Nonetheless, the results from this study are quite promising, particularly when coupled with results from the wider literature. It is well known that instability can be improved with training (Tarita-Nistor et al., 2009) using a variety of different training protocols. Our data shows that the need for such training (at least on this task) may be minimal. Relative target motion across the retina (caused alternately by target or fixation-point motion) lead to small increases in thresholds, but on a scale that is minimal when compared to the effect of stimulus duration. The relationship between thresholds and duration appeared to be highly similar across static/dynamic conditions, implying that similar processes are involved. We were therefore confident that our perceptual learning protocols would not be affected by instability to any great degree. Even if fixation instability was found to impair performance on more complex tasks, it is reasonably clear that it can be reduced through training (Nilsson et al., 2003; Tarita-Nistor et al., 2009; Seiple et al., 2005).

Knowing that this task is affected to a small extent by fixation instability, our next task was to determine whether or not our perceptual learning task would be affected in a sample of older observers with macular disease. We know from our crowding study that older observers should not be disproportionately affected by crowding, and previous studies (Kosnik et al., 1986) have shown that fixation stability is also largely age-invariant. While other factors may be involved, we can thus be confident that we have ruled

out two of the more likely variables that could affect thresholds in individuals with macular disease.

7.5 Macular Disease

There is widespread evidence for trained improvements in healthy peripheral vision, and our research has added to this. However, it is important to be aware that these improvements may not necessarily translate to individuals with macular disease. Specifically in our case, we could not know a priori that the perceptual learning we observed on the word-recognition task would be replicated in a sample of individuals with macular disease.

Recent studies on AMD demonstrated some improvements in perceptual tasks (Chung, 2011; Pijnacker et al., 2011). However, we should be cautious in our assessment of the findings of some of these studies. Recall that one of the concerns of our study is to demonstrate a program of perceptual learning that might have some external applicability. This is not the immediate concern of the bulk of the research in this field, although it is interesting to note that perceptual learning of some simple tasks (e.g. position discrimination, contrast detection, Vernier acuity) also appears to improve Snellen acuity (Zhou et al., 2006). This does not quite match up to our primary interest (in reading ability, which is more complex than Snellen or letter acuity) but it is quite promising. With this in mind, we tested participants on the MNRead acuity chart, alongside our word recognition perceptual learning protocol.

Participants recorded significant improvements in thresholds on the word recognition task, almost matching final thresholds of an age-matched normally sighted sample. The difference in final-day thresholds may have resulted from fixation instability, which (as noted in chapter 5) can lead to deficits in letter recognition.

Some transfer of learning to the more complex sentence reading task (MNRead) was also noted. This was interesting, because the stimuli in the

MNRead task were more crowded than those in the word recognition task. Similarly, the study reported above demonstrated between task learning from simple (e.g. position discrimination) to complex (Snellen acuity) tasks. If our finding holds, it may provide a simple, highly controlled training tool (i.e. word recognition) for improving peripheral reading ability. This also feeds into the wider debate around the use of different forms of training to ameliorate the effects of macular disease. Our data supports the use of perceptual learning protocols, though the precise aspects of the program that are important for generalised learning are still unclear.

In future, additional tests might also be used to demonstrate the external usefulness of any training protocol. The MNRead acuity chart was used in the current study, but it has been reported previously that it is affected by issues with its reliability (see Rubin (2013) for an analysis of this issue). One interesting alternative is the Sustained Reading Test (Ramulu, Swenor, Jefferys & Rubin, 2012), which would introduce considerable thoroughness to this type of research. The task uses 7000-word stories, read over 30 minutes, and is tested by questions of comprehension. It is thus an example of a task that is far more similar to natural reading, and should certainly be studied more closely.

7.6 Conclusions

This program of research had several clear aims. Our primary aim was to develop a program of perceptual learning capable of ameliorating some of the negative visual effects of macular disease (particularly deficits in reading ability). Informing this goal was a significant program of research that would help us to understand and shape the final program.

We approached this program of research with an open mind, as best evidence indicated that a variety of techniques might prove to be productive. Extensive testing indicated that training on a word recognition task led to highly significant, age-dependent improvements in thresholds.

The observed age-related differences in thresholds could be reduced by increasing the number of training sessions for older observers, supporting the view that perceptual learning is a prominent feature of the visual system throughout the lifespan (Ferchmin & Eterović, 1986; Mirmiran et al., 1996). This conclusion was further supported by the data from our AMD group, whose pattern of results was broadly similar to that of an age-matched sample.

A separate study suggested that crowding should not have unduly contributed to the age-dependence of the word-recognition results. However, the usable visual field of each individual AMD observer was quite different, so an increased effect of crowding for this group is possible. The upper visual field is known to be sub-optimal for reading (Watson et al., 2006), though we used it to maintain consistency across all of our studies. It is quite possible (indeed, likely) that an individually tailored site for training would lead to better results in a sample with macular disease.

Similarly, while our study on fixation has shown that fixation instability should not affect letter recognition, we cannot be certain of its effect on word recognition and sentence reading. Further testing, focused on word recognition in an AMD group, would be useful here.

In future, it would be useful to train a larger group of participants with AMD alongside a matched control group. The choice of control for this research is not simple. We have extensively used normally-sighted individuals in these experiments, but it is unclear if these are truly an appropriate comparison group. A lack of motivation (and potential structural dissimilarities) could affect results. The alternative is to use a control group with AMD (though recruitment is an issue) or else use a crossover design.

The choice of the MNRead task is also something that could be revised in future research. It is unclear if the improvements observed in this study exceed those of the expected test-retest variability. They exceed those of two previous studies, but are smaller than those of a third. The use of a matched

control group in future studies would help to clarify this issue. As reading has been our primary area of interest, it might also be interesting to examine reading comprehension, rather than just reading speed and acuity (though speed generally does not affect comprehension).

We have demonstrated some promising results, which may usefully inform further research in this field. We would like to reiterate the importance of behaviourally significant programs when working with this population – as previously noted, clinical measures of visual function may not have wider application, so we should always seek to ensure the relevance of any outcomes from new protocols. Nonetheless, the results of these studies indicate that further work along these lines may prove fruitful.

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Appendix A – Information sheet

Visual Neuroscience Group
School of Psychology
University Park
Nottingham
NG7 2RD

Exploiting Neural Plasticity in the Visual System of Older Adults

Investigators*: Alan Blighe, Dr. Ben Webb, Prof. Paul McGraw*

Healthy Volunteer's Information Sheet

You have been invited to take part in a research study. Before you decide whether to take part it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with friends and relatives if you wish to. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether you wish to take part or not. If you decide to take part you may keep this leaflet.

Background

Age-Related Macular Degeneration is a condition in which central vision degenerates in one eye, or occasionally both eyes. It accounts for 20,000 new cases of registered blindness every year in the UK, and its incidence has risen steadily over the last 50 years. At present there is no effective form of treatment. Instead, individuals with this condition are encouraged to develop a number of practical coping strategies (such as viewing objects of interest with peripheral regions of the eye). This study aims to provide information which may help to develop a new treatment method involving perceptual learning in peripheral vision. Perceptual learning refers to the marked improvements in visual performance that can be achieved through practice or training on certain visual tasks. Our long-term objective is to train and improve peripheral vision to a functional level of performance.

What does the study involve?

We will ask you to attend on 10 consecutive days (excluding weekends), or on only 2 days, spaced 10 days apart. These options represent two different experimental conditions we are using.

The first visit will involve a check on your spectacles if you wear any, followed by measurements of visual functions. The visual tasks are non-invasive and simply involve you making simple visual judgements on a target presented on a computer screen. For example, in one task you will be asked to indicate the orientation of a letter C. Please note that this does not constitute a full eye test. We are not in a position to diagnose serious eye problems, so you should still keep your regular check-up appointments as normal.

Subsequent sessions will involve training on a particular visual task. During the final session your performance on the tasks measured in the first session will be re-measured to determine whether training has produced any improvement.

The first and last sessions will last approximately 1 hour. All other sessions (training sessions) will last no more than 30 minutes.

Where does the study take place?

This study will take place in the School of Psychology, at the University of Nottingham (NG7 2RD). You will be given further instructions on where to come should you decide to participate.

Why have you been chosen?

You are being considered for this study because you responded to one of our advertisements for study subjects.

Do you have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part *you are still free to withdraw at any time and without giving a reason.*

Should you decide to participate in the study, you will be given a sum of money as a small thank you upon completion of the testing sessions – either £60 for the 10 day trial, or £15 for the 2 day trial.

Confidentiality

All information which is collected about you during the course of the research will be kept on a password protected database and is strictly confidential. Any information about you which leaves the research unit will have your name and address removed so that you cannot be recognised from it.

What will happen to the results of the research study?

The results from this study will be published in peer-reviewed journals, conference posters as well as the primary investigator's PhD thesis. Personal details of all subjects will be removed from all public dissemination of the results.

Who is organising and funding the research

This study is organised by School of Psychology at the University of Nottingham, and is funded by Age UK.

Contact for Further Information

If you have any further questions, please contact Alan Blighe on (0115) 951 5292, or at lpxab4@nottingham.ac.uk.

Thank you for showing interest in this study.

Appendix B – Consent form

Visual Neuroscience Group
School of Psychology

The University of Nottingham

Title of Project:

Exploiting Neural Plasticity in the Visual System of Older Adults

Name of Investigators:
Alan Blighe, Dr. Ben Webb, Prof. Paul McGraw

Healthy Volunteer's Consent Form

Please read this form and sign it once one of the above named people has explained fully the aims and procedures of the study to you

- I voluntarily agree to take part in this study.
- I confirm that I have been given a full explanation by the above named and that I have read and understand the information sheet given to me, which is attached.
- I have been given the opportunity to ask questions and discuss the study with one of the above investigators on all aspects of the study and have understood the advice and information given as a result.
- I agree to comply with the reasonable instructions of the supervising investigator and will notify him immediately of any unexpected unusual symptoms or deterioration of health.
- I authorise the investigators to disclose the results of my participation in the study but not my name.
- I understand that information about me recorded during the study will be kept in a secure database. If data is transferred to others it will be made anonymous. Data will be kept for 7 years after the results of this study have been published.
- I authorise the investigators to disclose to me any abnormal test results. (Delete this if not applicable.)
- I understand that I can ask for further instructions or explanations at any time.
- I understand that I am free to withdraw from the study at any time, without having to give a reason for my withdrawal.

- I confirm that I have disclosed relevant medical information before the study.
- I shall receive an inconvenience allowance of £60. If I withdraw from the study for medical reasons not associated with the study, payment will be made to me proportional to the length of the period of participation. However, if I withdraw for any other reason, payment will be forfeited.

"This study has been explained to me to my satisfaction, and I agree to take part. I understand that I am free to withdraw at any time".

Name: .....

Address: .....

Telephone number: .....

Signature: ..... **Date:** .....

I confirm that I have fully explained the purpose of the study and what is involved to:

.....

I have given the above named a copy of this form together with the information sheet.

Investigators Signature: ..... **Name:** .....

Study Volunteer Number: .....

Appendix C – Mini Mental State Exam

Participant . . . . . .
Examiner . . . . . .
Date . . . . . .

MINI-MENTAL STATE

Maximum Score	Score	
		ORIENTATION
5	( )	What is the (year) (season) (date) (day) (month)?
5	( )	Where are we: (country) (county) (town) (hospital) (floor).
		REGISTRATION
3	( )	Name 3 objects: 1 second to say each. Then ask the patient all 3 after you have said them. Give 1 point for each correct answer. Then repeat them until he learns all 3. Count trials and record. Trials: ( )
		ATTENTION AND CALCULATION
5	( )	Serial 7's. One point for each correct. Stop after 5 answers. Alternatively spell "world" backwards.
		RECALL
3	( )	Ask for the 3 objects repeated above. Give 1 point for each correct.
		LANGUAGE
9	( )	Name a pencil, and watch (2 points). Repeat the following "No ifs, ands or buts." (1 point) Follow a 3-stage command: "Take a paper in your right hand, fold it in half, and put it on the floor" (3 points) Read and obey the following: CLOSE YOUR EYES (1 point) Write a sentence (1 point) Copy design (1 point)

_____ **Total score**

ASSESS level of consciousness along a continuum: _____
Alert Drowsy Stupor Coma

INSTRUCTIONS FOR ADMINISTRATION OF MINI-MENTAL STATE EXAMINATION

ORIENTATION

(1) Ask for the date. Then ask specifically for parts omitted, e.g., "Can you also tell me what season it is?" One point for each correct.
(2) Ask in turn "Can you tell me the name of this hospital?" (town, county, etc.). One point for each correct.

REGISTRATION

Ask the patient if you may test his memory. Then say the names of 3 unrelated objects, clearly and slowly, about one second for each. After you have said all 3, ask him to repeat them. This first repetition determines his score (O-3) but keep saying them until he can repeat all 3, up to 6 trials. If he does not eventually learn all 3, recall cannot be meaningfully tested.

ATTENTION AND CALCULATION

Ask the patient to begin with 100 and count backwards by 7. Stop after 5 subtractions (93, 86,79,72,65). Score the total number of correct answers.
If the patient cannot or will not perform this task, ask him to spell the word "world" backwards. The score is the number of letters in correct order. E.g. dlrow = 5, dlorw = 3.

RECALL

Ask the patient if he can recall the 3 words you previously asked him to remember. Score O-3.

LANGUAGE

Naming: Show the patient a wrist watch and ask him what it is. Repeat for pencil. Score O-2.
Repetition: Ask the patient to repeat the sentence after you. Allow only one trial. Score 0 or 1.
3-Stage command: Give the patient a piece of plain blank paper and repeat the command. Score 1 point for each part correctly executed.
Reading: On a blank piece of paper print the sentence "Close your eyes", in letters large enough for the patient to see clearly. Ask him to read it and do what it says. Score 1 point only if he actually closes his eyes.
Writing: Give the patient a blank piece of paper and ask him to write a sentence for you. Do not dictate a sentence, it is to be written spontaneously. It must contain a subject and verb and be sensible. Correct grammar and punctuation are not necessary.
Copying: *On* a clean piece of paper, draw intersecting pentagons, each side about 1 in., and ask him to copy it exactly as it is. All 10 angles must be present and 2 must intersect to score 1 point. Tremor and rotation are ignored.

Estimate the patient's level of sensorium along a continuum, from alert on the left to coma on the right.

Mean = 27.6 ± 1.7
Range: 24 → 30